DYNAMIC PERFORMANCE OF DFIG WIND TURBINE UNDER UNBALANCE GRID FAULT CONDITION

A THESIS SUBMITTED IN PARTIAL FULFILLMENT OF THE REQUIREMENTS FOR THE DEGREE OF

Master of Technology
In
Power Control and Drives

By

KISHOR THAKRE

Department of Electrical Engineering

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Under the Guidance of

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NATIONAL INSTITUTE OF TECHNOLOGY
ROURKELA

CERTIFICATE

This is to certify that the thesis report entitled "**Dynamic performance of DFIG wind turbine under unbalance grid fault condition**" submitted by **Kishor Thakre**, has been carried out under my super vision in partial fulfillment of the requirements of the degree of Master of Technology with specialization in "Power Control and Drives" during session 2008-2009 in the Department of Electrical Engineering, National Institute of Technology, Rourkela (Deemed University) and this work has not been submitted elsewhere for a degree.

To the best of my knowledge, the matter embodied in the thesis has not been submitted to any other university/institute for the award of any degree.

Date:

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Kishor Thakre

Roll- No. - 207EE212

CONTENTS

Dedicated to

my

Late brother

ABSTRACT

The global electrical energy consumption is rising and there is steady increase of the demand on power generation. So in addition to conventional power generation units a large no. of renewable energy units is being integrated into the power system. A wind electrical generation system is the most cost competitive of all the environmentally clean and safe renewable energy sources in world. The recent evolution of power semiconductors and variable frequency drive technology has aided the acceptance of variable speed generation systems.

Both fixed-speed squirrel-cage induction generator and variable speed double fed induction generator are used in wind turbine generation technology. Therefore, a detailed model of induction generator coupled to wind turbine system is presented in the thesis. Modeling and simulation of induction machine using vector control computing technique is done in MATLAB/SIMULINK platform. The significant result of the analysis is also shown and being compared with the existing literature to validate approach.

DFIG–wind turbine is an integrated part of distributed generation system. Therefore, any abnormalities associates with grid are going to affect the system performance considerably.
Taking this into account, the performance of double fed induction generator (DFIG) variable speed wind turbine under network fault is studied using simulation developed in MATLAB/SIMULINK results show the transient behavior of the double fed induction generator when a sudden short circuit at the generator. After the clearance the short circuit fault the control schemes manage to restore the wind turbine's normal operation. The controller performance is demonstrated by simulation result both during fault and the clearance of the fault. A crowbar is used to protect the rotor converter against short-circuit current during faults.

LIST OF FIGURES

NOMENCLATURE

v_{ds} , v_{qs}	Stator *d* and *q* winding voltage.
i_{ds} , i_{qs}	Stator *d* and *q* winding current.
v_{dr} , v_{qr}	Rotor *d* and *q* winding voltage.
i_{dr} , i_{qr}	Rotor *d* and *q* winding current.
ψ_{ds}, ψ_{qs}	Stator *d* and *q* winding flux linkage.
ψ_{dr}, ψ_{qr}	Rotor *d* and *q* winding flux linkage
T_e	Electromagnetic torque.
T_m	Mechanical torque
Q_s	Stator reactive power.
P_s	Stator active power
L_m	Generator magnetizing inductance.
L_s , L_r	Stator and rotor per phase winding inductance.
L_{ls} , L_{lr}	Stator and rotor per phase leakage inductance.
R_s , R_r	Stator and rotor per phase winding resistance.
p	Number of generator poles.
H	System moment of inertia.
B	System frictional constant.
ω	Synchronous rotational speed (50 Hz).
ω_r	Rotor mechanical speed.
ω_b	Base speed

CHAPTER 1

INTRODUCTION

Introduction

Literature Survey

Motivation

Objective and thesis outline

1.1 INTRODUCTION

Wind energy generation equipment is most often installed in remote, rural areas. These remote areas usually have weak grids, often with voltage unbalances and under voltage conditions. When the stator phase voltages supplied by the grid are unbalanced, the torque produced by the induction generator is not constant. Instead, the torque has periodic pulsations at twice the grid frequency, which can result in acoustic noise at low levels and at high levels can damage the rotor shaft, gearbox, or blade assembly. Also an induction generator connected to an unbalanced grid will draw unbalanced current. These unbalanced current tend to magnify the grid voltage unbalance and cause over current problems as well.

Wind energy has been the subject of much recent research and development. In order to overcome the problems associated with fixed speed wind turbine system and to maximize the wind energy capture, many new wind farms will employ variable speed wind turbine. DFIG (Double Fed Induction Generator) is one of the component of Variable speed wind turbine system. DFIG offers several advantages when compared with fixed speed generators including speed control. These merits are primarily achieved via control of the rotor side converter. Many works have been proposed for studying the behavior of DFIG based wind turbine system connected to the grid. Most existing models widely use vector control Double Fed Induction Generator. The stator is directly connected to the grid and the rotor is fed to magnetize the machine.

Wind electrical power system are recently getting lot of attention, because they are cost competitive, environmental clean and safe renewable power sources, as compared fossil fuel and nuclear power generation.

The reason for the world wide interest in developing wind generation plants is the rapidly increasing demand for electrical energy and the consequent depletion reserves of fossil fuels, namely, oil and coal. Many places also do not have the potential for generating hydel power. Nuclear power generation was once treated with great optimism, but with the knowledge of the environmental hazard with the possible leakage from nuclear power plants, most countries have decided not to install them anymore.

The growing awareness of these problems led to heightened research efforts for developing alternative of energy sources for generation of electricity. The most desirable source would be one that non-pollutant, available in abundance and renewable and can be harnessed at an acceptable cost in both large-scale and small scale system. The most promising source satisfying all these requirement is wind, a natural source energy source.

The development of wind energy for electrical power generation got a boost when, in the early decades of the twentieth century, aviation technology resulted in an improved understanding of the forces acting on the blades moving through air. This resulted in the development of wind turbine with two or three blades. High speed and high efficiency of turbines were the condition for successful electricity generation. Through the efforts of countless scientists and engineer from various disciplines, wind energy has now matured as an economically viable renewable source of energy.

Wind energy is one of the most available and exploitable forms of renewable energy. Wind blows from a region of higher atmospheric pressure to one of the lower atmospheric pressure. The difference in pressure is caused by (A) the fact that earth’s surface is not uniformly heated by the sun and (B) the earth’s rotation. Wind energy is the by product of solar energy, available in the form of the kinetics energy of air. Wind has been known to man as a natural source of mechanical power for long. The technology of wind power has evolved over this long period. Of the various renewable energy sources, wind energy has emerged as the most viable source of electrical power and is economically competitive with conventional sources.

The global electrical energy is rising and there is a steady rise of the demand on power generation, transmission, distribution and utilization. The maximum extractable energy from the 0-100m layer of air has been estimated to be the order of 10^{12} KWh/annum, which is of the same order as hydroelectric potential.

The terms “wind energy” or “wind power” describe the process by which the wind is used to generate mechanical power or electricity. Wind turbines convert the kinetic energy in the wind into mechanical power. This mechanical power can be used for specific tasks (such as grinding gain or pumping water) or a generator can convert this mechanical power into electricity.

Since earliest recorded history, wind power has been used to move ships, grind grain and pump water. This is the evidence that wind energy was used to propel boats along the Nile River as early 5000 B.C. within several centuries before Christ, simple windmills were used in china to pump water.

In the United States, millions of windmills were erected as the American West was developed during the late 19th century. Most of them were used to pump water for farms and ranches. By 1900, small electric wind systems were developed to generate current, but most of these units fail into disuse as inexpensive grid power was extended to rural areas during the 1930s. By 1910, wind turbine generators were producing electricity in many European countries.

Wind turbines are available in a variety of size, and therefore power ratings. The largest machine, such as the one built in Hawaii, has propellers that span the more than the length of a football field and stands 20 building stories high, and produces enough electricity to power 1400 homes. A small home-sized wind machine has rotors between 8 and 25 feet in diameter and stands upwards of 30 feet and can supply the power needs of an all-electric home or small business.

All electric-generating wind turbines, no matter what size, are comprised of a few basic components: the (the part that actually rotates in the wind), the electrical generator, a speed control system, and a tower. Some wind machine have fail- safe shutdown system so that if part of the machine fails, the shutdown system turn the blades out of the wind or puts brakes.

Just like solar electric system, wind powered system can be used in two ways: off-grid or on-grid is when your home or business is entirely disconnected from electric utility company and you generate absolutely all of the electricity you need. Usually these systems cost about 30% more than an on-grid (or ‘grid-tie system). A grid tie wind power system sends all of its electricity back into the public electrical network (grid) which the electric company gives you credits for. At the month, the electric company sums up your credits with how much your home or consumed, and if you’re lucky the electric company will owe you money! Most electric companies only pay you a small fraction of what they change you for those kilowatt-you’ve created. So it’s usually ideal to design a system that very closely offsets how much electricity you consume or just little less, than attempting to make money from the electric company.

Benefits of wind power:

A wind energy system can provide a cushion against electric power price increases. Wind energy systems help reduces U.S. dependence on fossil fuels; and they are nonpolluting. If you live in a remote location, a small wind energy system could help you avoid the high costs of having utility power lines extended to your site. Although wind energy system involves a significant initial investment, they can be competitive with conventional energy sources when you account for a lifetime of reduced or altogether avoided utility costs. The length of the payback period – the time before the savings resulting from your system equal the cost of the system itself- depends on the system you choose the wind resource on your site, electricity costs in your area, and how you use your wind system.

Small wind energy systems can be used in connection with an electricity transmission and distribution system (called grid-connected systems), or in stand-alone application that are not connected to the utility grid. A grid-connected wind turbine can reduce consumption of utility-supplied electricity for lighting, appliances, and electric heat. If the turbine cannot deliver the amount of energy you need, the utility makes up the difference. When the wind system produces more electricity than the household requires, the excess can be returned to the grid. With the interconnection available today, switching takes place automatically. Stand-alone wind energy systems can be appropriate for homes, farms, or even entire communities (a co-housing project, for example) that are far from the nearest utility lines.

Either type of the system can be practical if the following condition exist

These are the few requirements of wind generation system:

- Wind generation is dependent on the quality and quantity of the wind hitting the blades. The better the wind you have the more power you will generate.
- The power available in wind increases by the cube of the wind speed – if wind speed doubles, power output increases by eight.

- Turbulent wind (from obstruction, geographical features, etc.) will reduce the power output as the turbine swings back and forth hunting for the wind.

  These are the few requirements of site for wind generation system:

- The higher a turbine, the more power is generated, the better quality the wind.
- A wind turbine should be at least 40 ft above any object within a 400 ft radius. Note there is often exception to this rule depending on your site.
- It is often more economical to install a higher tower than purchasing a larger turbine.
- Space: generally locations with an acre or more will be suitable. Most urban location will not permit you to install a wind generator in your yard. A guyed tower requires ½ the height of the tower as a radius at a minimum for location of anchor points. Space is also required for ground assembly and erection of the tower. Lattice towers require less surface area, but are more complex and expensive to install.

A special type of induction generator, called a doubly fed induction generator (DFIG), is used extensively for high-power wind applications (Fig. 3.4). DFIG's ability to control rotor currents allows for reactive power control and variable speed operation, so it can operate at maximum efficiency over a wide range of wind speeds. The Doubly-Fed Induction Generator (DFIG) is widely used for variable-speed generation, and it is one of the most important generators for Wind Energy Conversion Systems (WECS). Both grid connected and stand-alone operation is feasible. For variable speed operation, the standard power electronics interface consists of a rotor and stator side PWM inverters that are connected back-to-back. These inverters are rated, for restricted speed range operation, to a fraction of the machine rated power. Applying vector control techniques yields current control with high dynamic response. In grid-connected applications, the DFIG may be installed in remote, rural areas where weak grids with unbalanced voltages are not uncommon. As reported in induction machines are particularly sensitive to unbalanced operation since localized heating can occur in the stator and the lifetime of the machine can be severely affected. Furthermore, negative-sequence currents in the machine produce pulsations in the electrical torque, increasing the acoustic noise and reducing the life span of the gearbox, blade assembly and other components of a typical WECS. To protect the machine, in some applications, DFIGs are disconnected from the grid when the phase-to-phase voltage unbalance is above 6%.

Controller design parameters for the operation of induction generators in unbalanced grids have been reported in, where it is proposed to inject compensating current in the DFIG rotor to eliminate or reduce torque pulsations. The main disadvantage of this method is that the stator current unbalance is not eliminated. Therefore, even when the torque pulsations are reduced, the induction machine power output is rerated, because the machine current limit is reached by only one of the stator phase. Compensation of unbalanced voltages and currents in power systems are addressed in where a STATCOM is used to compensate voltage unbalances. However, the application of the control method to DFIGs is not discussed. No formal methodology for the design of the control systems is presented and only simulation results are discussed in. In this thesis, a controller design is specified, which compensates the stator current unbalance in grid-connected and stand-alone DFIG operation. The strategy uses two revolving axes theory (rotating synchronously at $\pm\omega_e$) to obtain the d–q components of the negative and positive-sequence currents in the stator and grid/load. The unbalance is compensated by the rotor side converter. The positive-sequence current is conventionally controlled to regulate the dc link voltage, whereas negative-sequence current is regulated to reduce or eliminate the grid voltage unbalance.   This work also includes some methods like:

- The modeling of a DFIG for unbalanced operation is presented. This model can be used to study the effects of negative-sequence components in the machine, e.g. torque pulsations in the electrical torque, ripple in the machine flux, etc., The modeling presented in Section 3 is suitable for analyzing DFIGs feeding unbalanced loads as well as DFIGs connected to unbalanced, weak grids.

- The control systems, based on two synchronously rotating axes, are presented and fully analyzed.

- The control systems, suitable for compensating the effects of negative-sequence components in a DFIG connected to an unbalanced grid are discussed. Grid-connected operation is considered as the most important application of DFIG.

1.2 LITERATURE SURVEY

In [1] the DFIG control strategy that enhances the standard speed and reactive power control with controllers that can compensate for the problems caused by an unbalanced grid by balancing the stator currents and eliminating torque and reactive power pulsations.

[2] Describe the controller to be controlled in positive and negative sequence independently. In order to implement the separated positive and negative sequence controllers of DFIG, two methods to separate positive and negative sequence in real time are compared.

[3] Presents a centralized supervision of the reactive power control for a wind farm. A weighting distribution strategy has been used in order to determine the reactive power reference for each wind generator.

[4] Explain a novel control strategy to overcome these problems; furthermore, it reduces the rotor voltage, improving the control of the rotor current and it accelerates the dumping of the flux oscillations.

[5] Explain a new methodology to compensate the stator voltage unbalance of DFIG has been proposed. The effects of voltage unbalances in DFIG have been discussed, equivalent circuits and small-signal models, appropriate to design the current control loops, have been proposed. Experimental results have been presented to validate the proposed control methodology. For stand-alone and grid-connected applications the performance of the control system has been tested considering variable-speed operation, fixed-speed operation and step connection of unbalanced loads.

[6] A technique is described which the objective to keep the generator has connected to the grid in case of a grid failure so that it can resume power generation after clearance of the fault in the grid. The key of the technique is to limit the high currents and to provide a bypass for it in the rotor circuit via a set of resistors that are connected to the rotor windings without disconnecting

the converter from the rotor or from the grid. The wind turbine can resume normal operation within a few hundred milliseconds after the fault has been cleared.

[7] Describe the two alternative fault detection methods, namely the Absolute Normalized DC Current Method and the Sampling Point Comparison Method. The former method provides similar fault detection capability while requiring less computational time than the Modified Normalized DC Current Method.

[8] Describes the dynamic behavior of a typical fixed speed wind turbine connected to the grid; the model is developed in the simulation tool MATLAB/SIMULINK and created as a modular structure. The pitch control system is used for stabilization of the wind turbine at grid faults. In this way, voltage stability of the system with grid-connected wind turbines can be improved by using blade angle control for a temporary reduction of the wind turbine power during a short-circuit fault in the grid

1.3 MOTIVATION

- Wind is intermittent
  - Limits wind's percentage of the energy mix.
  - Wind energy is often located in rural areas.
  - Rural grids are often weak and unstable, and prone to voltage sags, faults, and unbalances.

- Unbalanced grid voltages cause many problems for induction generators
  - Torque pulsations
  - Reactive power pulsations
  - Unbalanced currents

- Wind energy is often installed in rural, remote areas characterized by weak, unbalanced power transmission grids. In induction wind generators, unbalanced three-phase stator voltages cause a number of problems, such as over current, unbalanced currents, reactive power pulsations, and stress on the mechanical components from torque pulsations. Therefore, beyond a certain amount of unbalance, induction wind generators are switched out of the network. This can further weaken the grid. In doubly fed induction generators (DFIGs), control of the rotor currents allows for adjustable speed operation and reactive power control

1.4 OBJECTIVE AND THESIS OUTLINE

Objectives

- Doubly-fed induction generators are the machines of choice for large wind turbines in wind power generation.
- The objective is to develop a control methodology for a DFIG that can achieve:
- Observe the performance of double fed induction generator during balance and unbalance condition.
    - Variable speed and reactive power control
    - Compensation of problems caused by an unbalanced grid
        - Reduce torque pulsations
        - Reduce reactive power pulsations
        - Balance stator currents

Thesis outline

Chapter -2 deals with induction machine with basic dynamic d-q model, axes transformation and also describe dc drive analogy and vector control of induction machine in brief.

Chapter-3 deals with modeling of wind turbine, rotor side controller, double fed induction generator and also deals with detail modeling of wind turbine coupled with DFIG. Detail modeling of DFIG with dc motor drive has been discussed in brief.

Chapter-4 deals with DFIG under faults.

Chapter-5 deals with simulation results in balance and unbalance conditions.

CHAPTER 2

INDUCTION MACHINE

Introduction

Dynamic d-q model

Induction machine control

DC drive analogy

Principle of vector control

2.1 INTRODUCTION

Variable speed ac drives have been used in the past to perform relatively undemanding roles in application which preclude the use of dc motors, either because of the working environment limits. Because of the high cost efficient, fast switching frequency static inverter. The lower cost of ac motors has also been a decisive economic factor in multi motor systems. However as a result of the progress in the field of power electronics, the continuing trend is towards cheaper and more effective power converters, and a single motor ac drives complete favorably on a purely economic basis with a dc drives.

Among the various ac drive systems, those which contain the cage induction motor have a particular cost advantage. The cage motor is simple and rugged and is one of the cheapest machines available at all power ratings. Owing to their excellent control capabilities, the variable speed drives incorporating ac motors and employing modern static converters and torque control can well complete with high performance four quadrant dc drives.

The Induction motors (IM) for many years have been regarded as the workhorse in industry. Recently, the induction motors were evolved from being a constant speed motors to a variable speed. In addition, the most famous method for controlling induction motor is by varying the stator voltage or frequency. To use this method, the ratio of the motor voltage and frequency should be approximately constant. With the invention of Field Orientated Control, the complex induction motor can be modeled as a DC motor by performing simple transformations. In a similar manner to a dc machine, in induction motor the armature winding is also on the rotor, while the field is generated by currents in the stator winding. However the rotor current is not directly derived from an external source but results from the emf induced in the winding as a result of the relative motion of the rotor conductors with respect to the stator field. In other words, the stator current is the source of both the magnetic field and armature current. In the most commonly used, squirrel cage motor, only the stator current can directly be controlled, since the rotor winding is not accessible. Optimal torque production condition are not inherent due to the absence of a fixed physical disposition between the stator and rotor fields, and the torque equation is non linear. In effect, independent and efficient control of the field and torque is not as simple and straightforward as in the dc motor.

The concept of the steady state torque control of an induction motor is extended to transient states of operation in the high performance, vector control ac drive system based on the field operation principle (FOP). The FOP defines condition for decoupling the field control from the torque control. A field oriented induction motor emulates a separately exited dc motor in two aspects:

- Both the magnetic field and torque developed in the motor can be controlled independently.
- Optimal condition for the torque production, resulting in the maximum torque per unit ampere, occurs in the motor both in steady state and in transient condition of operation.

2.2 DYNAMIC d-q MODEL

R.H. Park in 1920's proposed a model for synchronous machine with respect to stationary reference frame. H.C. Stanley in 1930's proposed a model for induction machine with respect to stationary reference frame. Later G. Bryon's proposed a transformation of both stator and rotor variables to a synchronously rotating reference frame that moves with the rotating magnetic field. Lastly Krause and Thomas proposed a model for induction machine with respect to stationary reference frame.

2.2.1 Axes transformation

Consider a three phase induction machine with stationary stator winding axes as-bs-cs with voltages v_{as} , v_{bs}, v_{cs} and with respect to the stationary ref. frame$(d^s$- $q^s)$, the voltages are referred as v_{ds}^s, v_{qs}^s . Let, v_{as} makes an angle θ with v_{qs}^s . [16]. Assume that the d^s - q^saxes are oriented at an angle θ. The voltages v_{ds}^s– v_{qs}^s can be resolved into as-bs-cs components.

$$\begin{bmatrix} v_{as} \\ v_{bs} \\ v_{cs} \end{bmatrix} = \begin{bmatrix} \cos\theta & \sin\theta & 1 \\ \cos(\theta - 120°) & \sin(\theta - 120°) & 1 \\ \cos(\theta + 120°) & \sin(\theta + 120°) & 1 \end{bmatrix} \begin{bmatrix} v_{qs}^s \\ v_{ds}^s \\ v_{os}^s \end{bmatrix} \qquad (2.1)$$

The corresponding inverse relation is

$$\begin{bmatrix} v_{qs}^s \\ v_{ds}^s \\ v_{0s}^s \end{bmatrix} = \begin{bmatrix} \cos\theta & \cos(\theta - 120°) & \cos(\theta + 120°) \\ \sin\theta & \sin(\theta - 120°) & \sin(\theta + 120°) \\ 0.5 & 0.5 & 0.5 \end{bmatrix} \begin{bmatrix} v_{as} \\ v_{bs} \\ v_{cs} \end{bmatrix} \tag{2.2}$$

The voltages on the d^s - q^s can be converted into d^e - q^e frame (synchronously rotating frame):

$$v_{qs}^e = v_{qs}^s \cos\theta_e - v_{ds}^s \sin\theta_e \tag{2.3}$$

$$v_{ds}^e = v_{qs}^s \sin\theta_e - v_{ds}^s \cos\theta_e \tag{2.4}$$

Resolving the rotating frame parameter into stationary frame:

$$v_{qs}^s = v_{qs} \cos\theta_e + v_{ds} \sin\theta_e \tag{2.5}$$

$$v_{ds}^s = - v_{qs} \sin\theta_e + v_{ds} \cos\theta_e \tag{2.6}$$

Let, $v_{as} = v_m \cos(\omega_e t + \emptyset)$ (2.7)

$$v_{bs} = v_m \cos\left(\omega_e t - \frac{2\pi}{3} + \emptyset\right) \tag{2.8}$$

$$v_{cs} = v_m \cos\left(\omega_e t + \frac{2\pi}{3} + \emptyset\right) \tag{2.9}$$

From equation:

$$v_{qs}^s = v_m \cos(\omega_e t + \emptyset) \tag{2.10}$$

$$v_{ds}^s = - v_m \sin(\omega_e t + \emptyset) \tag{2.11}$$

Form equation:

$$v_{qs} = v_m \cos \emptyset \tag{2.12}$$

$$v_{ds} = -v_m \sin \emptyset \tag{2.13}$$

This shows that the sinusoidal variables in a stationary frame appear as DC quantity.

$$\left|\bar{V}\right| = V_m \tag{2.14}$$

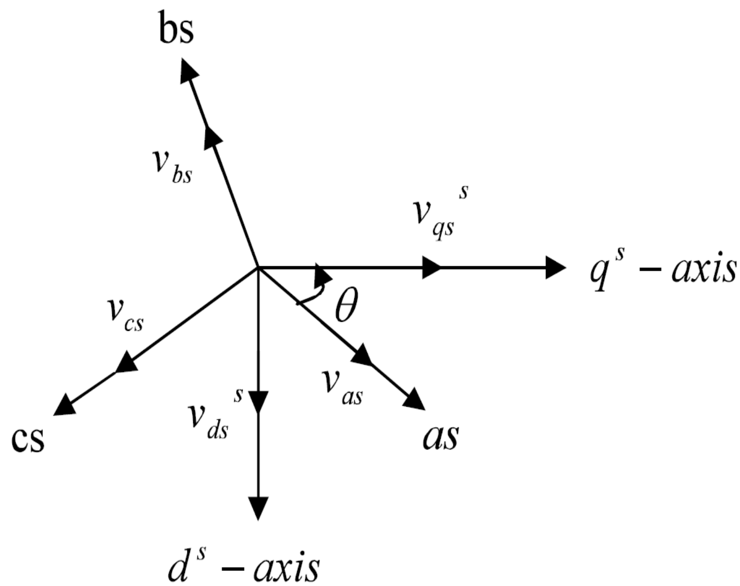


Fig. 2.1 Stationary frame a-b-c to d^s- q^s axes transformation

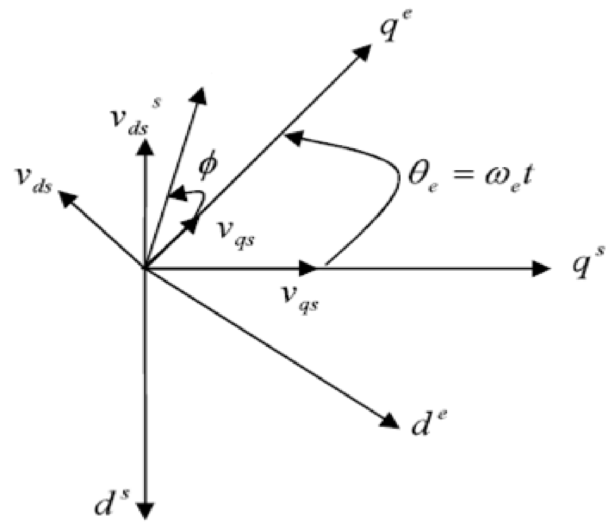


Fig. 2.2 Stationary frame d^s- q^s to synchronous rotating frame d^e-q^e

2.2.2 Synchronously rotating reference frame-Dynamic model (Kron's equation)

The stator circuit equations are:

$$v_{qs}^{s} = R_s i_{qs}^{s} + \frac{d}{dt}\psi_{qs}^{s} \tag{2.15}$$

$$v_{ds}^{s} = R_s i_{ds}^{s} + \frac{d}{dt}\psi_{ds}^{s} \tag{2.16}$$

Where, ψ_{qs}^{s} = q axis flux linkage

ψ_{ds}^{s} = d axis flux linkage

$$v_{qs} = R_s i_{qs} + \frac{d}{dt}\psi_{qs}^{s} + \omega_e \psi_{ds} \tag{2.17}$$

$$v_{ds} = R_s i_{ds} + \frac{d}{dt}\psi_{ds}^{s} - \omega_e \psi_{ds} \tag{2.18}$$

If the rotor is not rotating, the rotor equations will be written as:

$$v_{qr} = R_r i_{qr} + \frac{d}{dt}\psi_{qr}^{s} + \omega_e \psi_{dr} \tag{2.19}$$

$$v_{dr} = R_r i_{dr} + \frac{d}{dt}\psi^{s}_{dr} + \omega_e \psi_{qr} \tag{2.20}$$

If rotor rotates, then the equation will be:

$$v_{qr} = R_r i_{qr} + \frac{d}{dt}\psi^{s}_{qr} + (\omega_e - \omega_r)\psi_{dr} \tag{2.21}$$

$$v_{dr} = R_r i_{dr} + \frac{d}{dt}\psi^{s}_{dr} - (\omega_e - \omega_r)\psi_{qr} \tag{2.22}$$

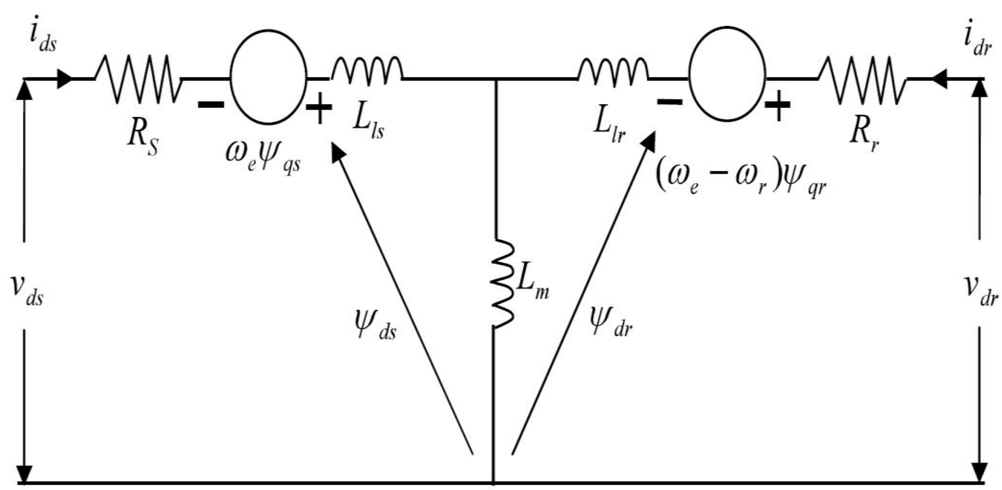


Fig. 2.3 Dynamic d^eaxis circuit

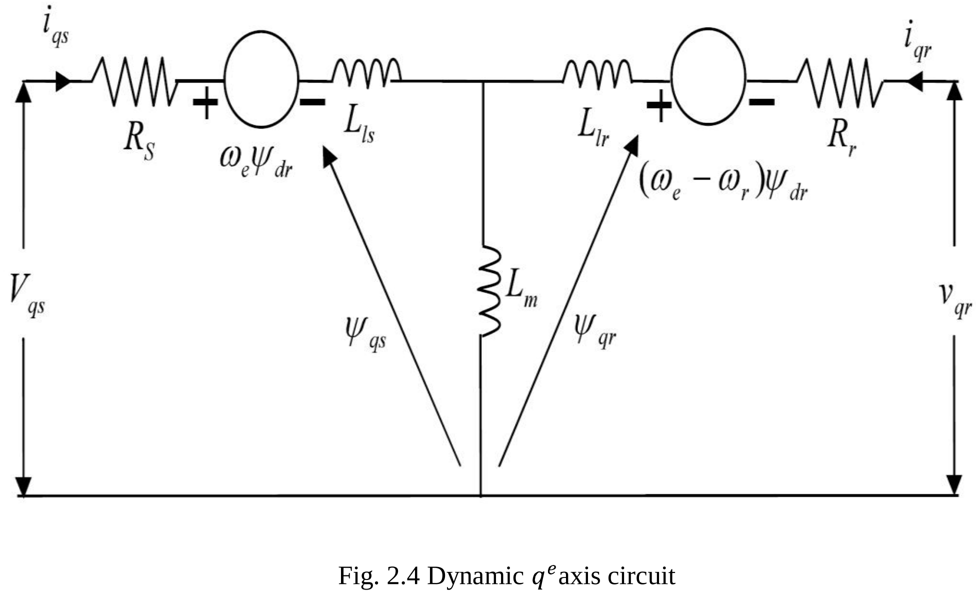


Fig. 2.4 Dynamic q^eaxis circuit

The flux linkage expressions in terms of the circuit currents are:

$$\psi_{qs} = L_{ls}\, i_{qs} + L_m\,(i_{qs}+i_{qr}) \tag{2.23}$$

$$\psi_{qr} = L_{lr}\, i_{qr} + L_m\,(i_{qs}+i_{qr}) \tag{2.24}$$

$$\psi_{ds} = L_{ls}\, i_{ds} + L_m\,(i_{ds}+i_{dr}) \tag{2.25}$$

$$\psi_{dr} = L_{lr}\, i_{dr} + L_m\,(i_{ds}+i_{dr}) \tag{2.26}$$

$$\psi_{qm} = L_m\,(i_{qs}+i_{qr}) \tag{2.27}$$

$$\psi_{dm} = L_m\,(i_{ds}+i_{dr}) \tag{2.28}$$

$$\begin{bmatrix} v_{qs} \\ v_{ds} \\ v_{qr} \\ v_{dr} \end{bmatrix} = \begin{bmatrix} R_s + SL_s & \omega_e L_s & SL_m & \omega_e L_m \\ -\omega_e L_s & R_s + SL_s & -\omega_e L_m & SL_m \\ SL_s & (\omega_e - \omega_{r)} L_m & R_r + SL_r & (\omega_e - \omega_r) L_r \\ -(\omega_e - \omega_r) L_m & SL_m & -(\omega_e - \omega_r) L_r & R_r + SL_r \end{bmatrix} \begin{bmatrix} i_{qs} \\ i_{ds} \\ i_{qr} \\ i_{dr} \end{bmatrix}$$

…………… (2.29)

The torque is given by:

$$T_e = \frac{3}{2}\left(\frac{P}{2}\right)\, \psi_m \times I_r \tag{2.30}$$

2.3 INDUCTION MACHINE CONTROL:

Squirrel cage induction machines are simple and rugged and are considered to be the workhorses of industry. However, the control structure of an induction motor is complicated since the stator field is revolving, and further complications arises due to the fact that the rotor currents or rotor flux of a squirrel cage induction motor can not be directly monitored The mechanism of torque production in an ac machine and in a dc machine is similar. Unfortunately this similarity was not emphasized before the 1970s, and this is one of the reasons why the technique of vector control did not emerge earlier. The formulae given in many well known textbook of the machine theory have also implied that, for the monitoring of the instantaneous electromagnetic torque of an induction machine, it is also necessary to monitor the rotor currents and the rotor position. Even in the 1980s some publications seemed to strengthen this false conception, which only arose because the complicated formulae derived for the expression of the instantaneous electromagnetic torque have not been simplified. However by using fundamental physical laws or space vector theory, it is easy to show that, similar to the expression of the electromagnetic torque of a separately exited dc machine, the instantaneous electromagnetic torque of an induction motor can be expressed as the product of a flux producing current and a torque producing current, if a special flux oriented reference is used.

2.3.1 Scalar control

Scalar control, as the name indicates, is due to magnitude variation of the control variables only, and disregarding the coupling effect in the machine. For example, the voltage of the machine can be controlled to control the flux, and the frequency and slip can be controlled to control the torque. However, flux and torque are also functions of frequency and voltage, respectively. Scalar control in contrast to the vector control or field oriented control, where both the magnitude and phase is controlled. Scalar controlled drives give some what inferior performance, but they are easily implemented. Scalar controlled drives have been widely used in industry. How ever their importance has diminished recently because of the superior performance of vector controlled drives, which is demanded in many applications.

2.3.2 Vector control or field oriented control

Scalar control is somewhat simple to implement, but the inherent coupling effect i.e. both torque and flux are functions of voltage or current and frequency gives the sluggish response and the system is easily prone to instability because of high order system harmonics. For example, if the torque is increased by incrementing the slip or slip the flux tends to decrease. The flux variation is sluggish. The flux variation then compensated by the sluggish flux control loop feeding additional voltage. This temporary dipping of flux reduces the torque sensitivity with slip and lengthens the system response time

These foregoing problems can be solved by vector control or field oriented control. The invention of vector control in the beginning of 1970s, and the demonstration that an induction motor can be controlled like a separately excited dc motor, brought a renaissance in the high performance control of ac drives. Because of dc machine like performance, vector control is known as decoupling, orthogonal, or Trans vector control. Vector control is applicable to both induction and synchronous motor drives. Vector control and the corresponding feedback signal processing, particularly for modern sensor less vector control, are complex and the use of powerful microcomputer or DSP is mandatory. It appears that eventually, vector control will oust scalar control, and will be accepted as the industry standard control for ac drives.

2.4 DC DRIVE ANALOGY

Ideally, a vector controlled induction motor drive operates like a separately excited dc motor drive in fig 2.5. In a dc machine, neglecting the armature reaction effect and field saturation, the developed torque is given by

$$T_e = K_t \psi_f \psi_a = K_t' I_f I_a \qquad (2.4.1)$$

Where, I_a = armature current

And I_f = field current

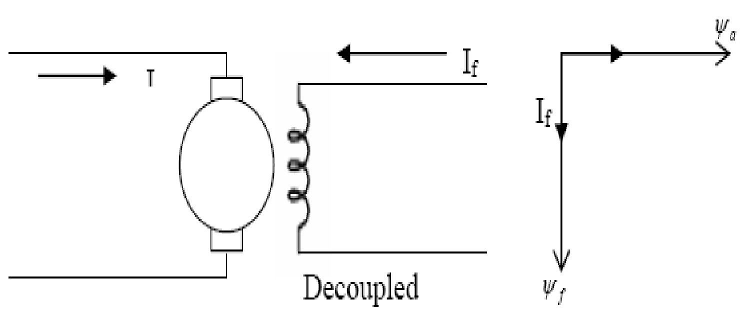


Fig. 2.5 separately exited DC motor

This construction of dc machine is such that the field flux ψ_f produced by the current I_f is perpendicular to the armature flux ψ_a,which is produced by the armature current. These space vectors, which are stationary in space, are orthogonal and decoupled in nature. This means that when torque is controlled by controlling the current I_a the flux ψ_f is not affected and we get the fast transient response and high torque ampere ratio. Because of decoupling, when the field current I_f is controlled, it affects the field flux ψ_f only, but not the ψ_a flux. Because of the inherent coupling problem, an induction motor can not generally give such fast response.

DC machine like performance can also be extended to an induction motor if the machine is considered in a synchronously rotating reference frame ($d^e - q^e$), where the sinusoidal variables appears as dc quantity in steady.

In fig 2.6, the induction motor with the inverter and vector control in the front end is shown with two control current inputs i_{ds}^* and i_{qs}^*.These currents are the direct axis component and quadrature axis component of the stator current, respectively, in a synchronously rotating reference frame.

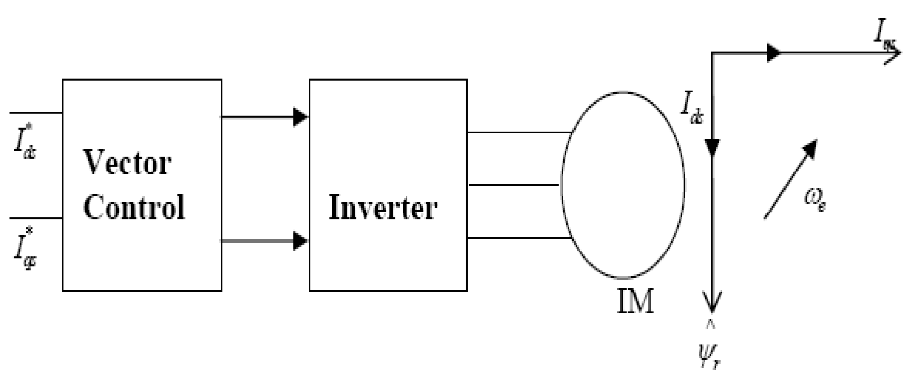


Fig. 2.6 vector controlled induction motor

With vector control, i_{ds} is analogous to field current I_f and i_{qs} is analogous to armature Current I_a of a dc machine. Therefore, the torque can be expressed as

$$T_e = K_t \hat{\psi}_r I_{qs} = K_t' I_{qs} I_{ds} \qquad (2.4.2)$$

Where, $\widehat{\psi}_r$ = absolute peak value of the sinusoidal space vector. This dc machine like performance is only possible if i_{ds} is oriented in the direction of $\widehat{\psi}_r$ and i_{qs} is established perpendicular to it, as shown by the space vector diagram of fig 2.2. This means that when i_{qs}^* is controlled; it affects the actual i_{qs} current only, but does not affect the flux $\widehat{\psi}_r$. Similarly, when i_{ds}^* is controlled, it controls the flux only and does not affect the i_{ds} component of current. This vector or field orientation of current is essential under all operating condition in a vector control drive. When compared to dc machine space vectors, induction machine space vector rotate synchronously at frequency ω_e as indicated in fig 2.2.

2.5 PRINCIPAL OF VECTOR CONTROL

The fundamentals of vector control implementation can be explained with the help of fig. 2.7 where the machine model is represented in a synchronously rotating reference frame. The inverter is omitted from the figure, assuming that it has unity current gain, that is, it generates currents $i_a, i_b,$ and i_c *as* dictated by the corresponding commands currents i_a^*, i_b^* and i_c^* from the controller. A machine model with internal conversions is shown on the right. The machine terminal phase currents i_a, i_b and i_c are converted to I_{ds}^s and I_{qs}^s component by $3\varphi/2\varphi$ transformation.

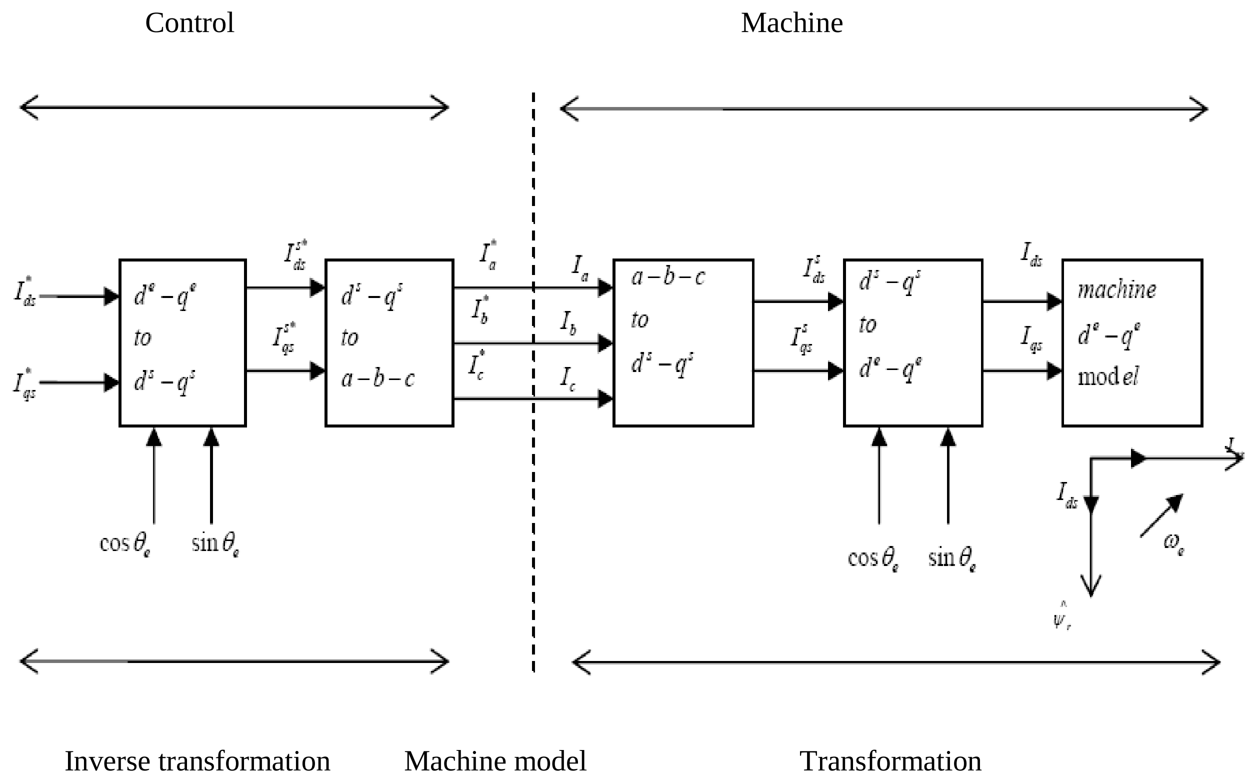


Fig. 2.7 vector control implementation principle with machine (d^e−q^e) model.

These are then converted to synchronously rotating frame by the unit vector components $\cos\theta_e$ and $\sin\theta_e$ before applying them to the d^e−q^e machine model as shown in the fig 1.3. The controller makes two stage of inverse transformation, as shown, so that the control currents i_{ds}^* and i_{qs}^* corresponds to the machine current i_{ds} and i_{qs} , respectively. The transformation and inverse transformation including the inverter ideally do not incorporate any dynamics therefore, the response to i_{ds} and i_{qs} is instantaneous.

CHAPTER 3

WIND TURBINE & DOUBLE FED INDUCTION GENERATOR

Wind turbine

Double fed induction generator

DFIG driven by dc machine

3.1 WIND TURBINE

Wind turbines convert aerodynamic power into electrical energy. In a wind turbine two conversion processes take place. The aerodynamic power (available in the wind) is first converted into mechanical power. Next, that mechanical power is converted into electrical power. Wind turbines can be either constant speed or variable speed generator. In this thesis only variable speed wind turbines will be considered.

Wind turbine basics - The mechanical power produced by a wind turbine is proportional to the cube of the wind speed. The rotational speed of the wind turbine for which maximum power is obtained is different for different wind speeds. Therefore variable speed operation is necessary to maximize the energy yield. Variable speed turbines are connected to the grid via a PEC that decouples the rotational speed of the wind turbine from the grid frequency, enabling variable speed operation. Two basic concepts exist for variable speed turbines. The first concept has a electric generator with a converter connected between the stator windings and the grid network shown in Fig. 3.2(a). The converter has to be designed for the rated power of the turbine. The generator is mostly a (permanent magnet) synchronous machine. Some types do not have a gearbox: the direct-drive concept. An alternative concept is a wind turbine with a doubly-fed induction generator (DFIG), which has a converter connected to the rotor windings of the wound-rotor induction machine, in Fig. 3.2(b). This converter can be designed for a fraction (~ 30%) of the rated power.

3.2 SYSTEM CONFIGURATION OF A VARIABLE-SPEED DFIG WIND TURBINE

To simulate a realistic response of a DFIG wind turbine subjected to power system faults, the main electrical components as well as the mechanical parts and the controllers have to be considered in the simulation model. The applied DFIG wind turbine model is the same as described in [4], [5], and therefore only briefly described here. Fig.3.2 (b) illustrates the block diagram of the main components of DFIG based wind turbines:

• Drive train and aerodynamics

• Pitch angle control system

Drive train and aerodynamics: A simplified aerodynamic model is sufficient to illustrate the effect of the speed and pitch angle changes on the aerodynamic power during grid faults. This simplified aerodynamic model is typically based on a two-dimensional aerodynamic torque coefficient C_q-table [18], provided by a standard aerodynamic program.

In stability analysis, when the system response to heavy disturbances is analyzed, the drive train system must be approximated by at least a two mass spring and damper model [20]. The turbine and generator masses are connected through a flexible shaft, which is characterized by a stiffness k and a damping c. The idea of using a two-mass mechanical model is to get a more accurate response from the generator and the power converter during grid faults and to have a more accurate prediction of the impact on the power system.

Pitch angle control system: The pitch angle control is realized by a PI controller. In order to get a realistic response in the pitch angle control system, the servomechanism model accounts for a servo time constant T_{servo} and a limitation of both the pitch angle and its rate-of-change, as illustrated in Fig.3.1. A gain scheduling control of the pitch angle is implemented in order to compensate for the nonlinear aerodynamic characteristics [18].

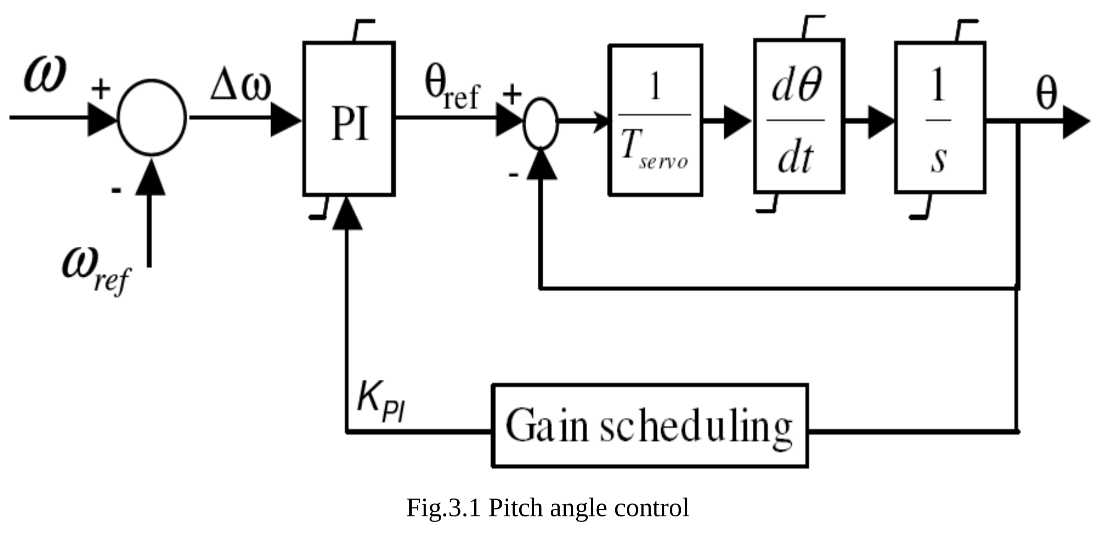
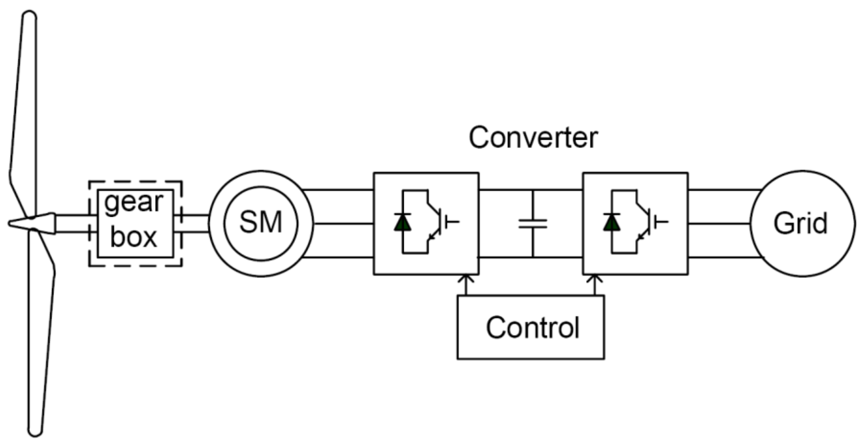


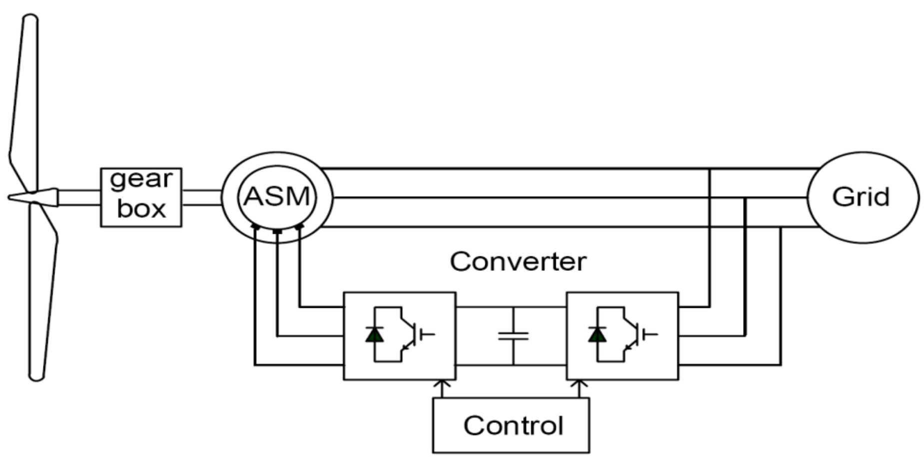
Fig.3.1 Pitch angle control

The rate-of-change limitation is very important during grid faults, because it decides how fast the aerodynamic power can be reduced in order to prevent over-speeding during faults. In this work, the pitch rate limit is set to a typical value of 10 deg/s.

Note that the pitch angle control, illustrated in Fig. 3.1 prevents over-speeding both in normal operation and during grid faults, due to the fact that the pitch angle controls directly the generator speed. In case of over-speeding, the aerodynamic power is automatically reduced while the speed is controlled to its rated value. This means that there is no need to design an additional pitch control solution as it is done in [21] and [22] to improve the dynamic stability during grid fault



(a)



(b)

Fig. 3.2 Variable speed wind turbines:
(a) With full-size converter; (b) with doubly-fed induction generator

Characteristics and interface –The output power of the wind turbine is not controllable. Due to the large inertia of the wind turbine blades, the output power of the turbine will vary slowly. In case of wind turbines with a full converter the response to grid events is mainly determined by the PEC. In case of a turbine with a DFIG the response is a mix of the induction machine response and the converter response.

Damping: In normal operation, the active power set-point P_{ref}^{grid} for the rotor side converter is defined by the maximum power tracking point (MPT) look-up table as function of the optimal generator speed [18], [19]. In case of a grid fault, the active power set point P_{ref}^{grid} is defined as the output of a damping controller, which has as task to damp the torsion oscillations, which are excited in the drive train due to the grid fault. When a fault is detected, the definition of the active power set-point P_{ref}^{grid} is switched between the normal operation definition (i.e. MPT) and the fault operation definition (damping controller).

As illustrated in Fig. 3.3, the PI damping controller produces the active power reference signal for the rotor side converter control, based on the deviation between the actual generator speed and its reference [20]. The speed reference is defined by the optimal speed curve at the incoming wind. The damping controller is tuned to damp actively the torsion oscillations excited at a grid fault in the drive train system. The pitch control system, illustrated in Fig. 3.1, is not able to damp the torsion oscillations, because of several delay mechanisms in the pitch [23]. In contrast to this, the damping controller acting on the fast power converter control is able to damp the fast oscillations in the generator speed.

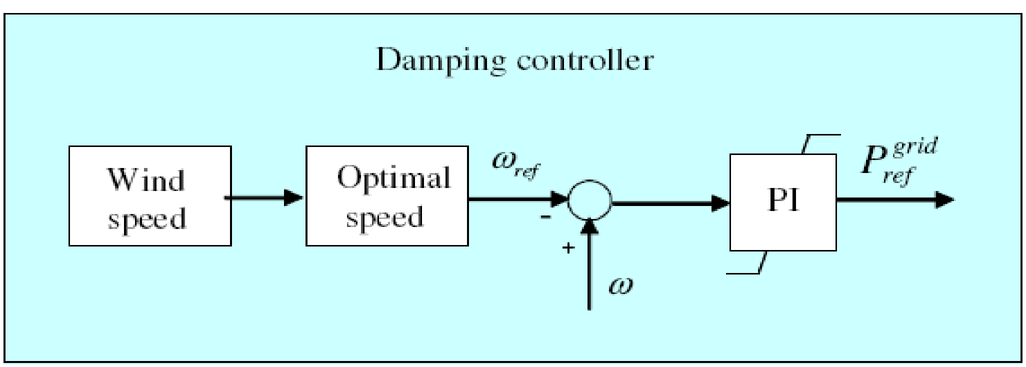


Fig.3.3 damping controller

3.2.1 Wind turbine modeling

In wind parks, many wind turbines are equipped with fixed frequency induction generators. Thus the power generated is not optimized for all wind conditions. To operate a wind turbine at its optimum at different wind speeds, the wind turbine should be operated at its maximum power coefficient ($C_{P.optimum}$= 0.3-0.5). To operate around its maximum power coefficient, the wind turbine should be operated at a constant tip-speed ratio, which is proportional to ratio of the rotor speed to the wind speed. As the wind speed increases, the rotor speed should follow the variation of the wind speed. In general, the load to the wind turbine is regulated as a cube function of the rotor rpm to operate the wind turbine at the optimum efficiency. The aerodynamic power generated by wind turbine can be written as:

$$P = 0.5\rho A C_p v^3 \tag{3.1}$$

Where the aerodynamic power is expressed as a function of the specific density **(ρ)** of the air, the swept area of the blades **(A)** and the wind speed (v). To operate the wind turbine at its optimum efficiency ($C_{P.optimum}$) the rotor speed must be varied in the same proportion as the wind-speed variation. If we can track the wind speed precisely, the power can also be expressed in terms of the rotor speed. The Simulink model is shown in fig. 3.3 by using equation [3.2] and generates the mechanical power.

$$P = K_p\ \omega^3 \tag{3.2}$$

The power described by equation [3.2] will be called P_{idel}. This is the power to be generated by the generator at different rotor rpm. One way to convert a wind turbine from fixed speed operation to variable-speed operation is to modify the system from a utility-connected induction generator to a self excited operation. Ideally if the inertia of the wind turbine rotor is negligible, the rotor speed can follow the variation of the wind speed if the output power of the generator is controlled to produce the power-speed characteristic described in equation 3.2. Thus the wind turbine will always operate at $C_{P.optimum}$. In reality, the wind turbine rotor has a significantly large inertia due to the blade inertia and other components. The wind turbine operation can only in the vicinity $C_{P.optimum}$. However, compared to fixed-speed operation, the energy captured in variable-speed operation is significantly higher.

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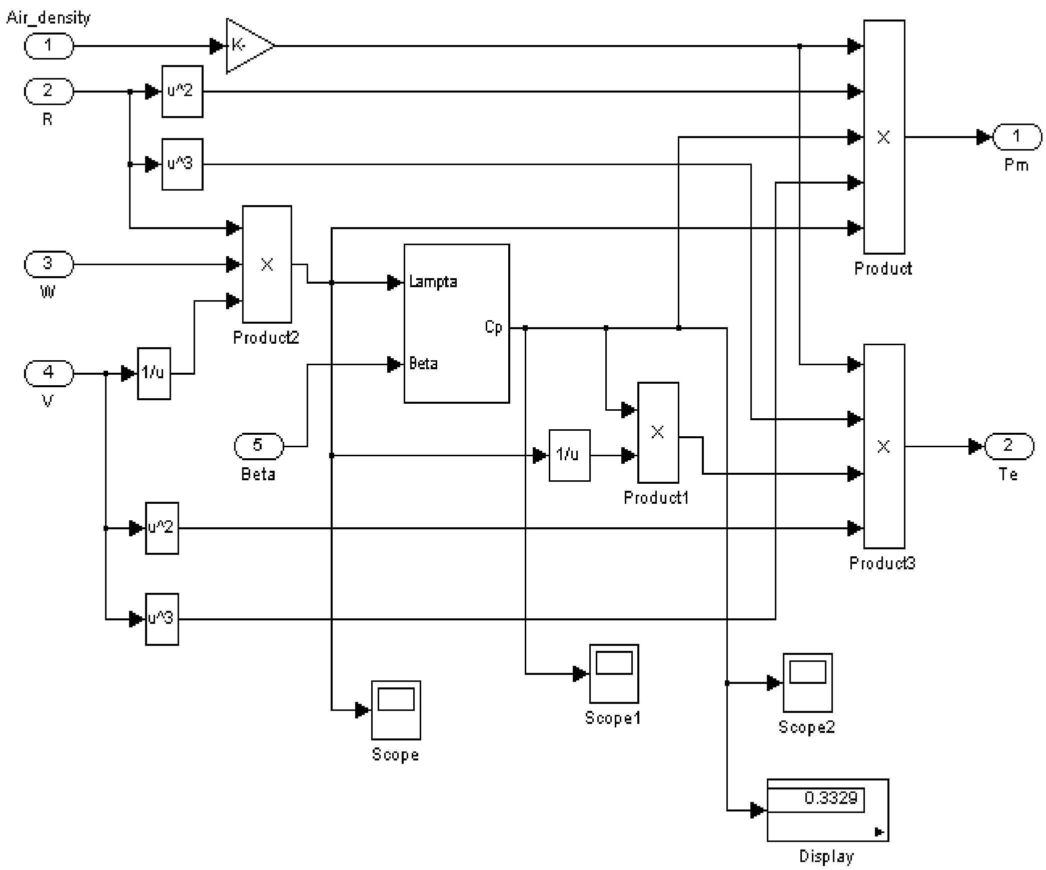


Fig. 3.4 Simulink model of wind turbine

With variable-speed operation and sufficiently large rotor inertia, there is a buffer between the energy source (wind) and energy sink (utility). Allowing the rotor speed to vary has the advantage of using the kinetic energy to be transferred in and out of the rotor inertia. Thus, the aerodynamic power that fluctuates with the wind input is filtered by the inertia before it is transmitted to the utility grid. This concept is very similar to the use of dc filter capacitor at the dc bus of a dc-dc converter. The dc capacitor filters the voltage ripple so that the voltage output presented to the load will be a smooth output voltage. It is expected that the turbulent content in wind input will not be transmitted directly to the mechanical drives (gearbox) of the wind turbines thus the mechanical stress and fatigues on mechanical components can be relieved. Thus, the lifetime of the mechanical drives and other components of the wind turbine can be extended by variable-speed operation.

3.3 DOUBLE FED INDUCTION GENERATOR

A double fed induction generator is a standard, wound rotor induction machine with its stator windings is directly connected to grid and its rotor windings is connected to the grid through an AC/DC/AC converter. AC/DC converter connected to rotor winding is called rotor side converter and another DC/AC is grid side converter. Doubly fed induction generator (DFIG), is used extensively for high-power wind applications (Fig. 3.4). DFIG's ability to control rotor currents allows for reactive power control and variable speed operation, so it can operate at maximum efficiency over a wide range of wind speeds. The research goal is to develop a control method and analysis to dynamic performance of DFIG's rotor control capabilities for unbalanced stator voltages, grid disturbances and dynamic load condition. This will allow DFIGs to stay connected to the grid under faulty conditions in which they would normally be disconnected for their own protection. In this thesis only rotor side converter control is considered. Grid side converter control is not considered in this analysis.

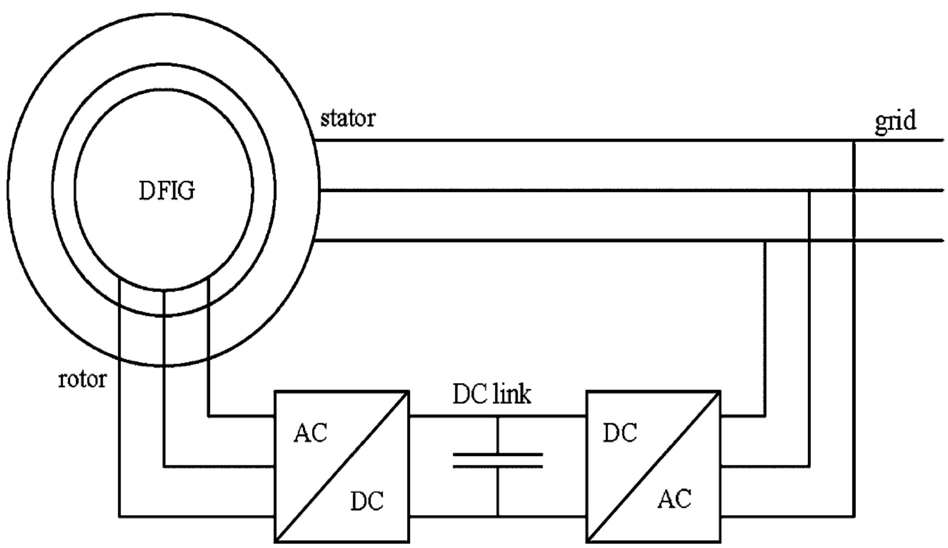


Fig.3.5 double fed induction machine

In modern DFIG designs, the frequency converter is built by self-commutated PWM converters, a machine-side converter, with an intermediate DC voltage link. Variable speed operation is obtained by injecting a variable voltage into the rotor at slip frequency. The injected rotor voltage is obtained using DC/AC insulated gate bipolar transistor based voltage source converters (VSC), linked by a DC bus. By controlling the converters, the DFIG characteristics can be adjusted so as to achieve maximum of effective power conversion or capturing capability for a wind turbine and to control its power generation with less fluctuation.

Power converters are usually controlled utilizing vector control techniques [24], which allow decoupled control of both active and reactive power. In normal operation the aim of the rotor side converter is to control independently the active and reactive power on the grid, while the grid side converter has to keep the dc-link capacitor voltage at a set value regardless of the magnitude and the direction of the rotor power and to guarantee a converter operation with unity power factor (zero reactive power).

Many different d-q control algorithms have been proposed and used for controlling the DFIG machine and grid-side converters for obtaining certain dynamic and transient performance of DFIGs. Most of them are based on a real and reactive power control concept, a popular DFIG converter control mechanism used in modern wind turbines. This control configuration is usually divided into machine and grid-side converter controls. The rotor-side converter controls the active and reactive power of the DFIG independently, and the grid-side converter is controlled in such a way as to maintain the DC-link capacitor voltage in a set value and to maintain the converter operation with a desired power factor.

The rotor side controller, consisting of a reactive power controller and an active power controller, is commonly a two stage controller as shown in Fig. 3.5 and also shown in fig. 3.6 the simulink model in MATLAB/SIMULINK.

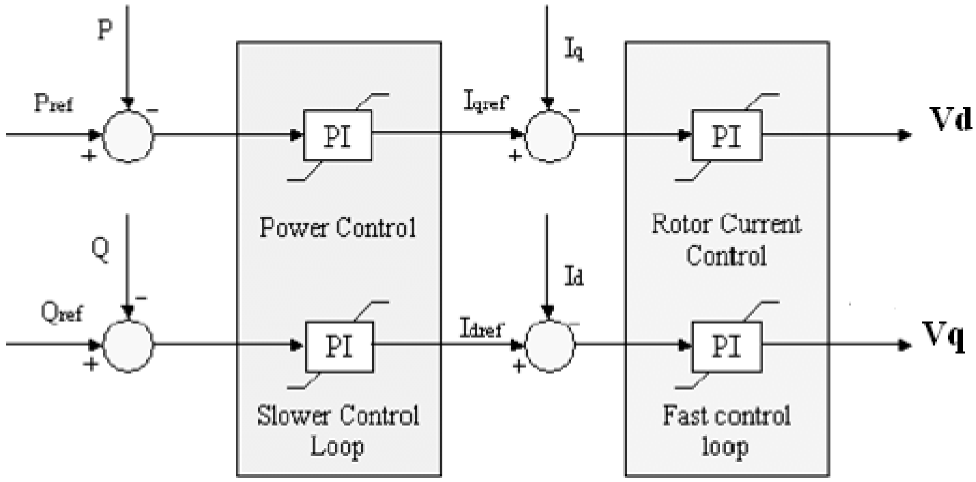


Fig.3.6 DFIG rotor side controller

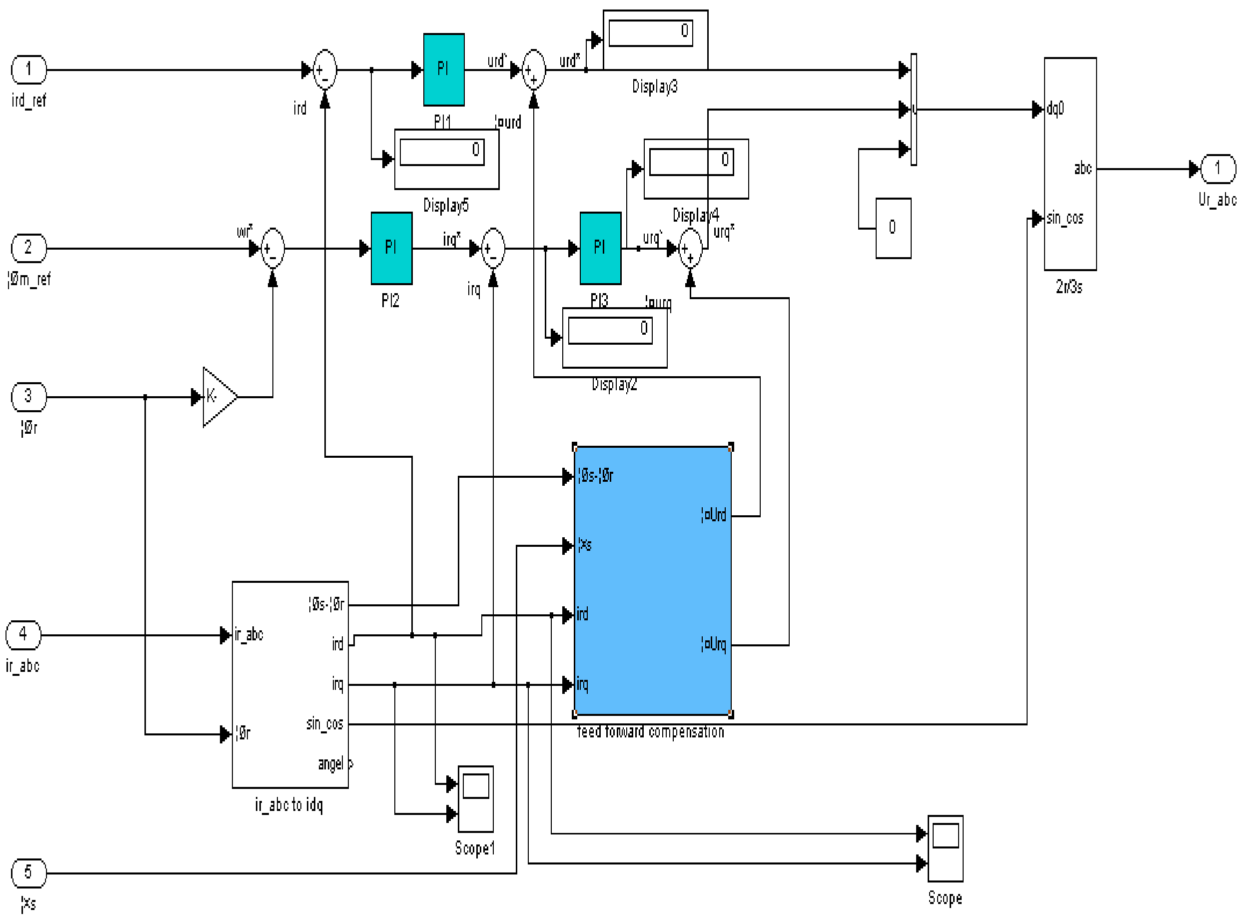


Fig. 3.7 simulink model of rotor side controller

It operates in either stator flux or stator-voltage oriented reference frame and hence the q-axis current component represents active power and the d-axis component represents reactive power. The two controllers in the machine-side controller determine inverter d- and q-voltages by comparing the d- and q-current set points to the actual d- and q- currents of the induction machine.

3.3.1 Modeling of DFIG

The voltage equations of an induction machine in an arbitrary reference frame can be written in terms of the currents as shown in Eq. (3.3)

$$\begin{bmatrix} v_{qs} \\ v_{ds} \\ v_{0s} \\ v'_{qr} \\ v'_{dr} \\ v'_{0r} \end{bmatrix} = \begin{bmatrix} R_s + \frac{P}{\omega_b}X_{ss} & \frac{\omega}{\omega_b}X_{ss} & 0 & \frac{P}{\omega_b}X_m & \frac{\omega}{\omega_b}X_m & 0 \\ -\frac{\omega}{\omega_b}X_{ss} & R_s + \frac{P}{\omega_b}X_{ss} & 0 & -\frac{\omega}{\omega_b}X_m & \frac{P}{\omega_b}X_m & 0 \\ 0 & 0 & R_s + \frac{P}{\omega_b}X_{ls} & 0 & 0 & 0 \\ -\frac{P}{\omega_b}X_m & \frac{\omega-\omega_r}{\omega_b}X_m & 0 & R_r + \frac{P}{\omega_b}X'_{rr} & \frac{\omega-\omega_r}{\omega_b}X'_{rr} & 0 \\ -\frac{\omega-\omega_r}{\omega_b}X_m & \frac{P}{\omega_b}X_m & 0 & -\frac{\omega-\omega_r}{\omega_b}X'_{rr} & R_r + \frac{P}{\omega_b}X'_{rr} & 0 \\ 0 & 0 & 0 & 0 & 0 & R_r + \frac{P}{\omega_b}X'_{lr} \end{bmatrix} \begin{bmatrix} i_{ds} \\ i_{ds} \\ i_{0s} \\ i'_{qr} \\ i'_{dr} \\ i'_{0r} \end{bmatrix} \quad \ldots\ldots (3.3)$$

where v_{qs} , v_{ds} are q-axis and d-axis stator voltages i_{qs} , i_{ds} are q-axis and d-axis stator currents, v'_{qr} , v'_{dr} , i'_{qr} and i'_{dr} are q-axis and d-axis rotor voltages and currents referred to the stator windings by appropriate turns ratio, ω is the rotating speed of the arbitrary reference frame, ω_r is the rotor speed, X_{ss} , X'_{rr} are stator and rotor self inductive reactance's, X_m is the mutual reactance, and, X_{ls} , X'_{rr} , R_s and R'_r are stator and rotor leakage reactances and resistances. If we select $\omega = \omega_b$ that is, the rotating speed of the reference frame work is same as $2\pi 60$ rad/s, this reference frame is called a synchronously rotating reference frame or synchronous reference frame. The air gap flux linkages ψ_{qm} and ψ_{dm} can be expressed as

$$\psi_{qm} = L_m\,(i_{qs} + i'_{qr}) \quad (3.4)$$

$$\psi_{dm} = L_m\,(i_{ds} + i'_{dr}) \quad (3.5)$$

And electromagnetic torque T_e can expressed as

$$T_e = \frac{3}{2}\left(\frac{p}{2}\right)\left(\psi_{qm}\, i_{dr} - \psi_{dm}\, i_{qr}\right) \tag{3.6}$$

Generally, the power losses associated with the stator resistance are small enough to be ignored; hence the approximation of electromagnetic power can be written as

Active power, $P_s = (v_{ds}\, i_{ds} - v_{ds}\, i_{ds})$ (3.7)

While the reactive power that the stator absorbs from, or injects into the power system can be calculated as

$$Q_s = \left(v_{qs}\, i_{ds} - v_{ds}\, i_{qs}\right) \tag{3.8}$$

Assume that the reference frame is the synchronous reference frame and that all quantities are in per unit value. Eq. (3.3) can be further written as:

$$\dot{X} = \mathrm{AX} + \mathrm{BU} \tag{3.9}$$

$$\text{Where X} = \begin{bmatrix} i_{ds} \\ i_{ds} \\ i_{0s} \\ i'_{qr} \\ i'_{dr} \\ i'_{0r} \end{bmatrix} \quad \text{and} \quad \text{B} = \begin{bmatrix} \frac{X_{ss}}{\omega_b} & 0 & 0 & \frac{X_m}{\omega_b} & 0 & 0 \\ 0 & \frac{X_{ss}}{\omega_b} & 0 & 0 & \frac{X_m}{\omega_b} & 0 \\ 0 & 0 & \frac{X_{ls}}{\omega_b} & 0 & 0 & 0 \\ \frac{X_m}{\omega_b} & 0 & 0 & \frac{X'_{rr}}{\omega_b} & 0 & 0 \\ 0 & \frac{X_m}{\omega_b} & 0 & 0 & \frac{X'_{rr}}{\omega_b} & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 \end{bmatrix}^{-1}$$

$$\text{A} = -\text{B}\begin{bmatrix} R_s & \frac{\omega}{\omega_b}X_{ss} & 0 & 0 & \frac{\omega}{\omega_b}X_m & 0 \\ -\frac{\omega}{\omega_b}X_{ss} & R_s & 0 & -\frac{\omega}{\omega_b}X_m & 0 & 0 \\ 0 & 0 & R_s & 0 & 0 & 0 \\ 0 & \frac{\omega-\omega_r}{\omega_b}X_m & 0 & R'_r & \frac{\omega-\omega_r}{\omega_b}X'_{rr} & 0 \\ -\frac{\omega-\omega_r}{\omega_b}X_m & 0 & 0 & \frac{\omega-\omega_r}{\omega_b}X'_{rr} & R'_r & 0 \\ 0 & 0 & 0 & 0 & 0 & R'_r \end{bmatrix}$$

……………. (3.10)

The swing equation is

$$T_e = 2\mathrm{H}\dot{\omega}_r + T_m \qquad (3.11)$$

Where T_m the mechanical torque and H is is the inertia.

The differential equations (3.3) and (3.11) represent the induction machine with its fifth-order model.

3.3.2 DFIG Simulink models

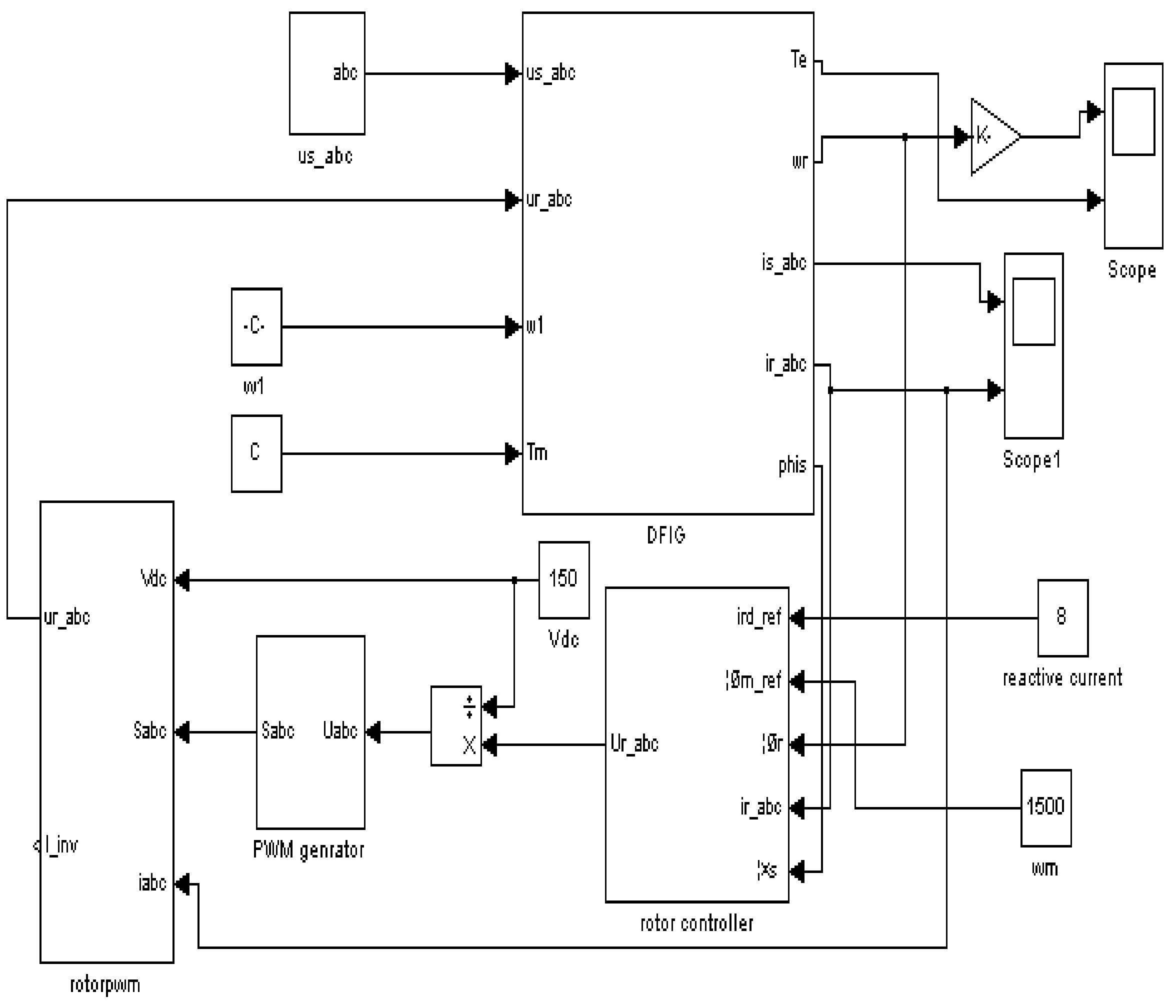


Fig. 3.8 detailed model in simulink of DFIG

The entire double fed induction generator model block consists of both the swing equation (3.11), current state space model from equation (3.3) and rotor side controller. The detailed model in MATLAB/SIMULINK platform is shown in Fig. 3.7. In this model block, the inputs are voltage and rotor speed, mechanical torque and the output is a current vector and electromagnetic torque. This model is quite simple and easy to understand.

3.4 DFIG DRIVEN BY DC MOTOR

Double fed induction generator driven by the dc machine. The DC motor has decoupled with double fed induction generator in stead of wind turbine. The simulation model of DC motor with DFIG shown in fig. 3.9 In this thesis another one thing analyze in stead of wind turbine the prime mover of induction generator has been connected with DC motor. And observe that the characteristics of current component vector and electromagnetic torque almost same with and without grid fault condition.

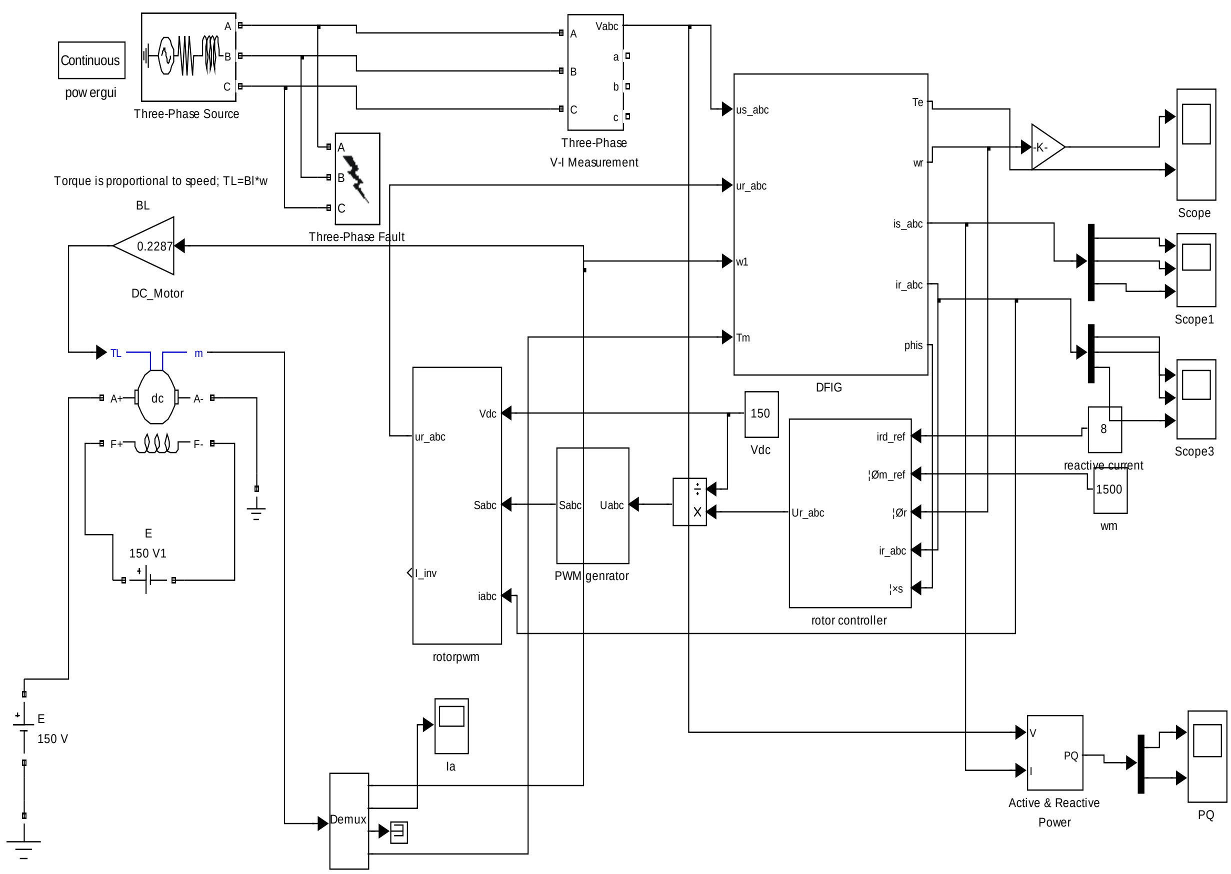


Fig. 3.9 simulink model of DFIG with DC motor with three phase fault

CHAPTER 4

DYNAMIC RESPONSE OF DFIG UNDER UNBALANCE CONDITION

Introduction

Double fed induction machine under fault

4.1 INTRODUCTION

Unbalance may be defined as in several views it can be voltage dip (also the word voltage sag is used) is a sudden reduction (between 10% and 90%) of the voltage at a point in the electrical system, and sudden change of load (dynamic load) .There can be many causes for a voltage dip: short circuits somewhere in the grid, switching operations associated with a temporary disconnection of a supply, the flow of the heavy currents that are caused by the start of large motor loads, or large currents drawn by arc furnaces or by transformer saturation. Voltage dips due to short-circuit faults cause the majority of equipment trip and therefore of most interest. Faults are either symmetrical (three-phase or three phase-to-ground faults) or nonsymmetrical (single-phase or double-phase or double-phase-to ground faults). Depending on the type of fault, the magnitudes of the voltage dips of each phase might be equal (symmetrical fault) or unequal (nonsymmetrical faults). The magnitude of a voltage dip at a certain point in the system depends mainly on the type of the fault, the distance to the fault, the system configuration, and the fault impedance.

The dynamics of the DFIG have two poorly damped poles in the transfer function of the machine, with an oscillation frequency close to the line frequency. These poles will cause oscillations in the flux if the doubly-fed induction machine is exposed to a grid disturbance. After such a disturbance, an increased rotor voltage will be needed to control the rotor currents. When this required voltage exceeds the voltage limit of the converter, it is not possible any longer to control the current as desired.

This implies that a voltage dip can cause high induced voltages or currents in the rotor circuit. The high currents might destroy the converter, if nothing is done to protect it. In Fig. 4, the rotor currents of the machine are shown for a voltage dip of 85%, implying, that only 15% of the grid voltage remains. The -axis and -axis component of the rotor current are shown in the figure. It can be seen that the rotor currents oscillates to about four times the rated current. If nothing is done to protect the converter, it will be destroyed completely.

4.2 DOUBLE FED INDUCTION MACHINE UNDER FAULTS

Consider DFIG in which, immediately after a 3-phase fault occurs, the stator voltage and flux reduces toward zero. The voltage drop depends, of course, on the location of the fault. The rotor current then increases to attempt to maintain the flux linkage within the rotor windings constant. DFIG under fault can be shown in fig. 4.1 However, for a DFIG the increase in the rotor current immediately after a fault will be determined by two factors. The first is the change in the stator flux and the second is the change in the rotor injected voltage.

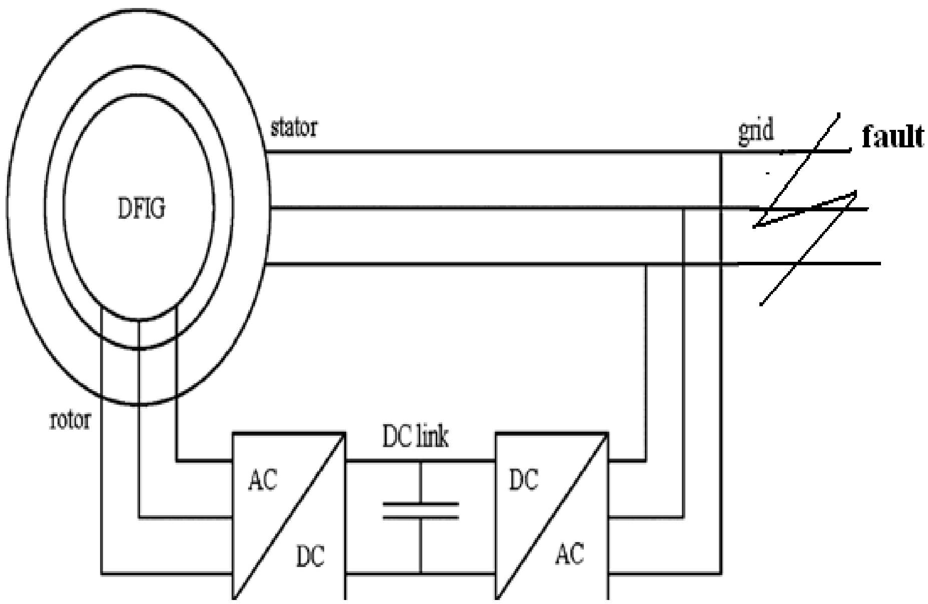


Fig. 4.1 block diagram of DFIG with fault in grid side

4.2.1 Behavior immediately after the fault

In the fault instant, the voltage at the DFIG generator terminal drops and it leads to a corresponding decrease of the stator and rotor flux in the generator. This results in a reduction of the electromagnetic torque and active power – see chapter 5 section 5.3. As the stator flux decreases, the magnetization that has been stored in the magnetic field has to be released. The generator starts thus its demagnetization over the stator, which is illustrated in Fig.5.3.5 by the reactive power peak in the moment of the fault.

In the fault moment, as the stator voltage decreases significantly, high current transients appear in the stator and rotor windings. As a demonstration the rotor current is plotted in Fig. 5.3.3 In order to compensate for the increasing rotor current, the rotor side converter increases the rotor voltage reference, which implies a "rush" of power from the rotor terminals through the converter. On the other side, as the grid voltage has dropped immediately after the fault, the grid side converter is not able to transfer the whole power from the rotor through the converter further to the grid. The grid side converter's control of the dc-voltage reaches thus quickly its limitation. As a result, the additional energy goes into charging the dc-bus capacitor and the dc-voltage rises rapidly.

4.2.2 Behavior at Fault Clearance

During the fault, the stator voltage and rotor flux have been reduced, the injected rotor voltage has been changed and the rotor speed has been increased. Immediately the fault is cleared the stator voltage is restored, and the demagnetized stator and rotor oppose this change in flux thus leading to an increase in the rotor and stator currents.

NOTE:

- The PI damping controller is tuned damping actively torsion oscillation observe during grid fault system in the drive train system. Damping controller acting fast power converter controlled. Damping controller provided the rotor side converter quickly damped out oscillation associate with a generator speed.
- Wind speed is to be constant during grid fault simulation.
- Monitoring DC link voltage and rotor current during grid disturbance a suitavle optimum protection system both for rotor side converter and DFIG can be design.

CHAPTER 5

SIMULATION RESULTS AND DISCUSSION

5.1 FREE ACCELERATION CHARACTERISTICS

5.1.1Curent component ~ Time

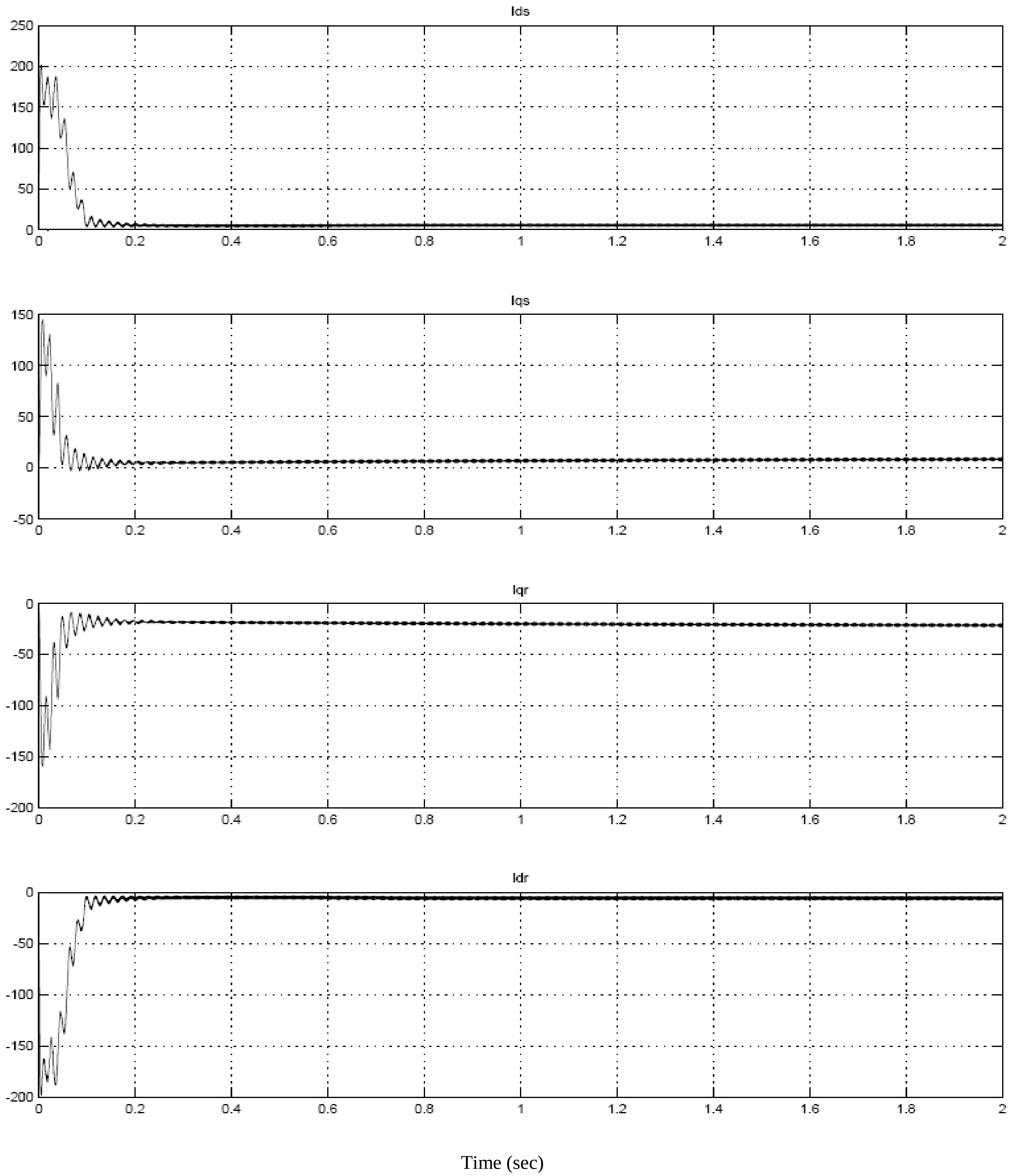


Fig. 5.1.1 free acceleration characteristics of current component ($i_{ds,}i_{qs,}$ $i_{qr,}$ $i_{qr,}$)

5.1.2 Speed ~ torque characteristics

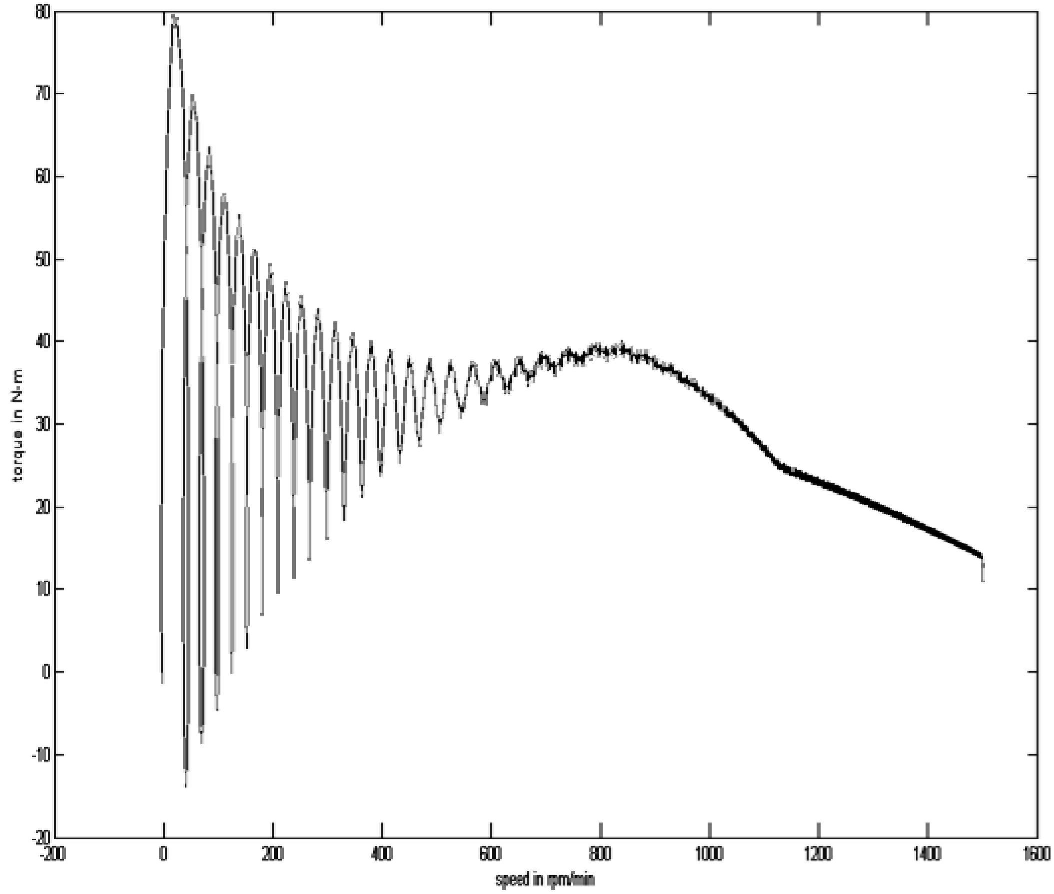


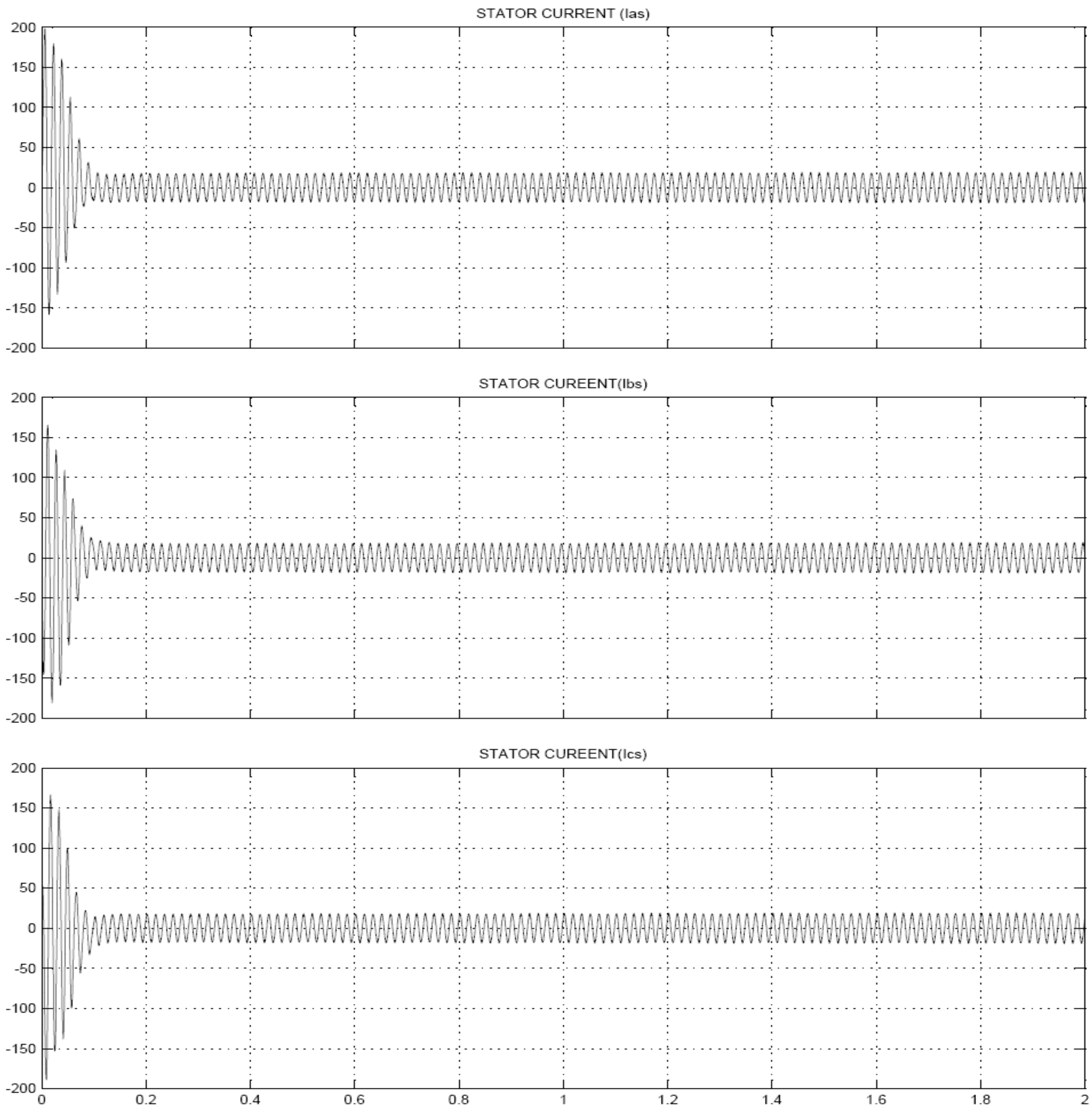
Fig. 5.1.2 speed- torque characteristics

Discussion: 5.1

The torque verses speed characteristics during free acceleration shown in fig. 5.1.2 when the induction generator is started, initially it shows transients and this region of operation is called as unstable region of operation due to inverting rotor voltage. After some time torque increases and a steady state is reached. Free acceleration with the reference frame of rotating in synchronism with the electrical speed of the applied voltage is shown in fig. 5.1.1 here the zero position of the reference is selected so that v_{qs} is the amplitude of the stator applied phase voltages and v_{ds}=0.

5.2 WIND TURBINE DFIG WITH NORMAL CONDITION

5.2.1 Stator currents ~ time



Time (sec)

Fig .5.2.1 stator currents ($i_{as,}i_{bs,}i_{cs,}$) during balance condition

5.2.2 Rotor currents ~ time

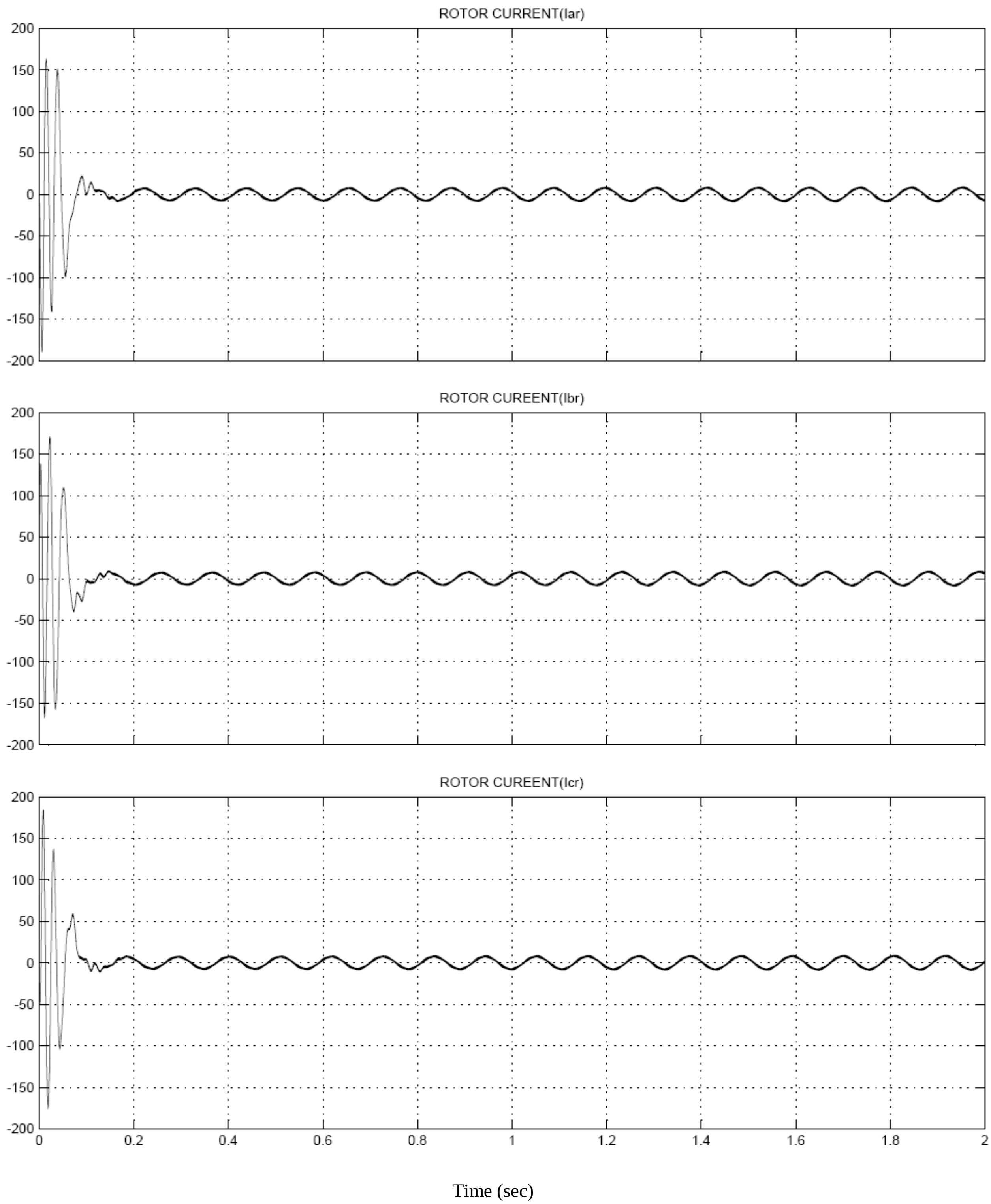
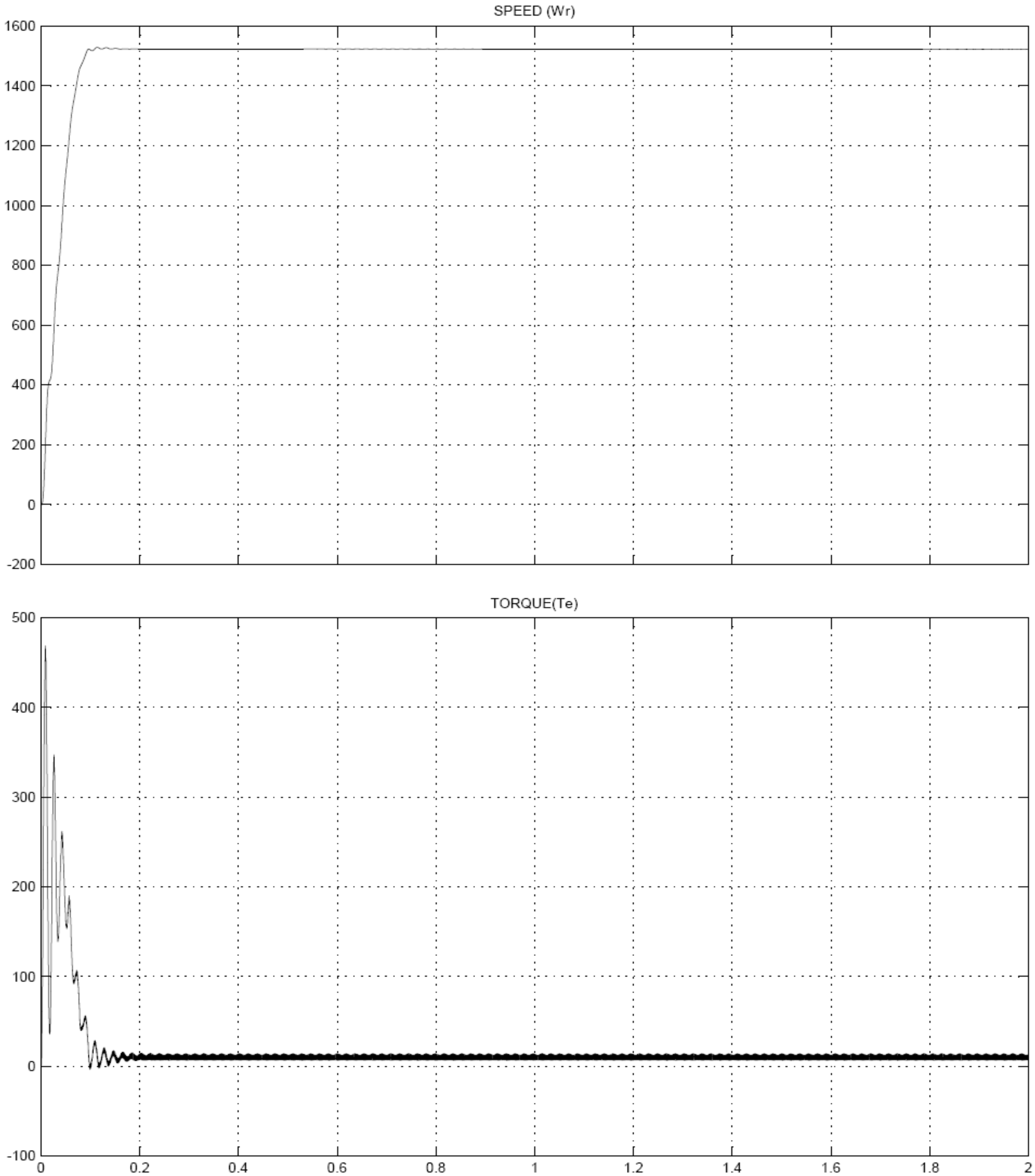


Fig. 5.2.2 rotor currents ($i_{ar,}i_{br,}i_{cr,}$) during balance condition

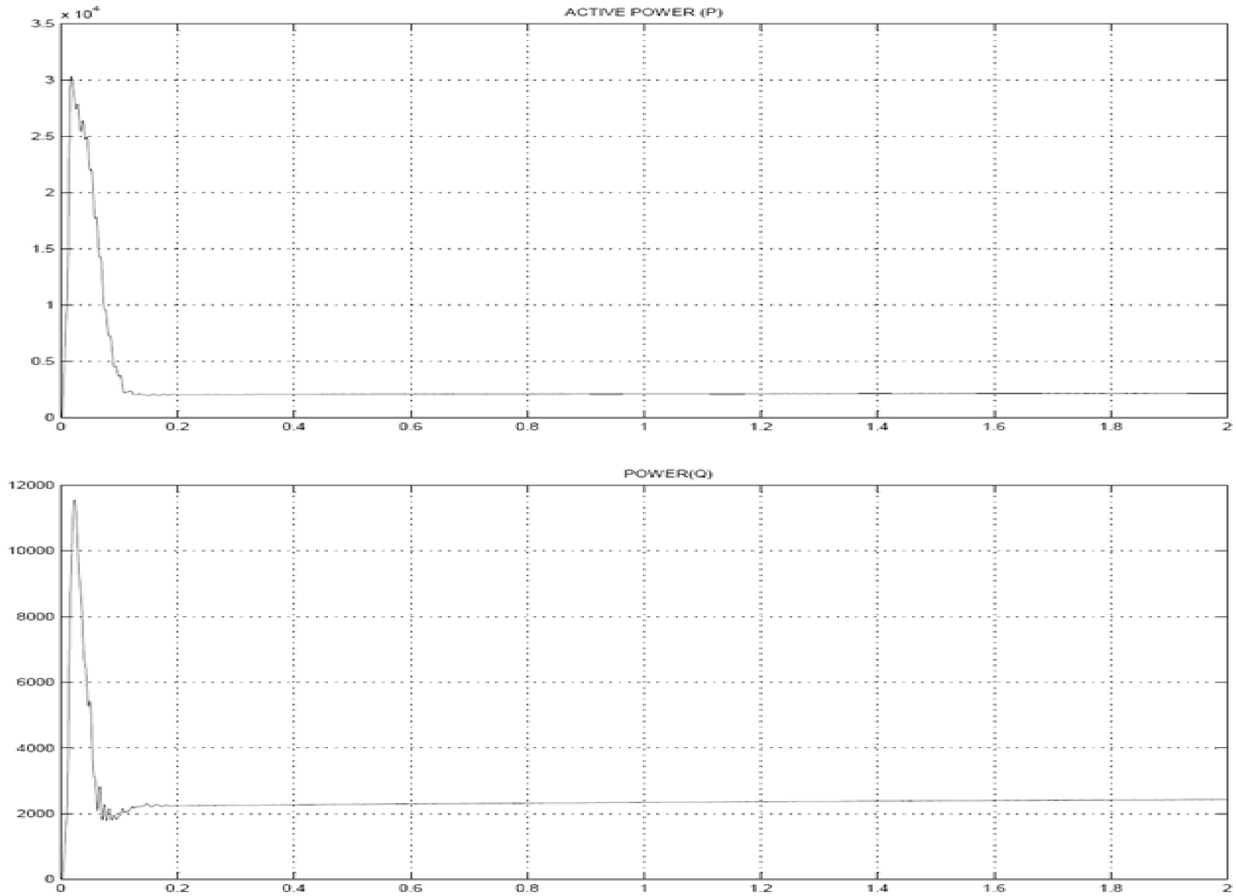
5.2.3 Speed and electromagnetic torque ~ time



Time (sec)

Fig. 5.2.3 speed and torque($\omega_r, T_{e,}$) during balance condition

5.2.4 Power characteristics ~ time



Time (sec)

Fig.5.2.4 active power (P) and reactive power (Q) during balance condition

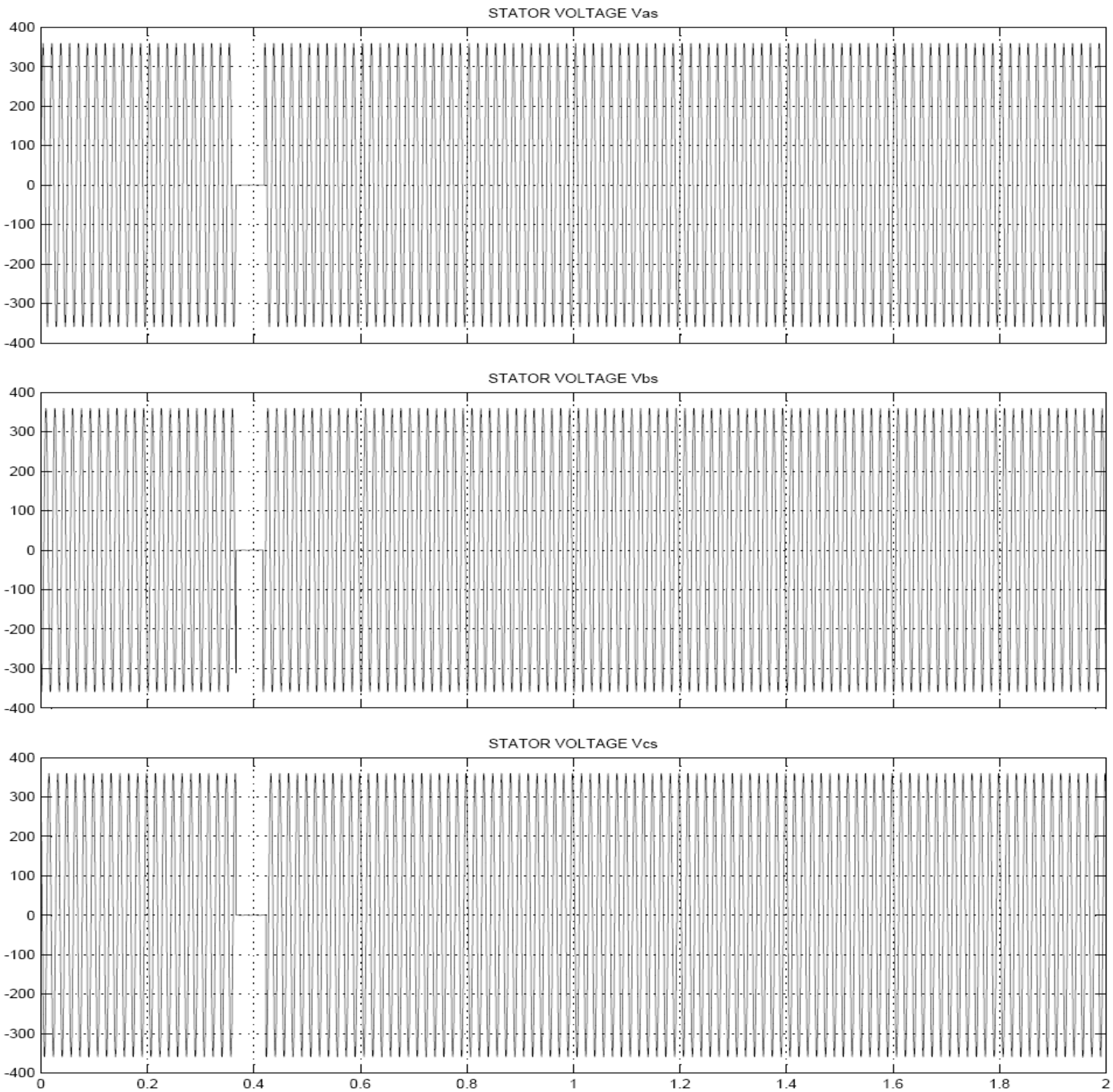
Discussion: 5.2

The transient torque and speed characteristics with time are different from the steady state torque and speed characteristics with time shown in fig.5.2.3 in several respects. The instantaneous electromagnetic torque following the application of the stator voltages varies at 60Hz about an average positive value. The decaying, 60 Hz variation in instantaneous torque is due to the transient offset in stator currents. Although the offset in each of the currents depends upon the value of source voltage at the time of application, the instantaneous torque is independent of the initial values of balanced source voltage because the machine is symmetrical. We also note from the currents plots shown in fig. 5.2.1 and fig. 5.2.2 that the envelope of the machine currents varies during transient period. It is shown in a subsequent that this due to the interaction of the stator and rotor electric transients.

5.3 WIND TURBINE DFIG DURING GRID FAULT

3.1 Stator voltages ~ time

→fault ←



Time (sec)

Fig. 5.3.1 stator voltages $v_{as,}v_{bs,}v_{cs,}$ during grid fault

5.3.2 Stator currents ~ time

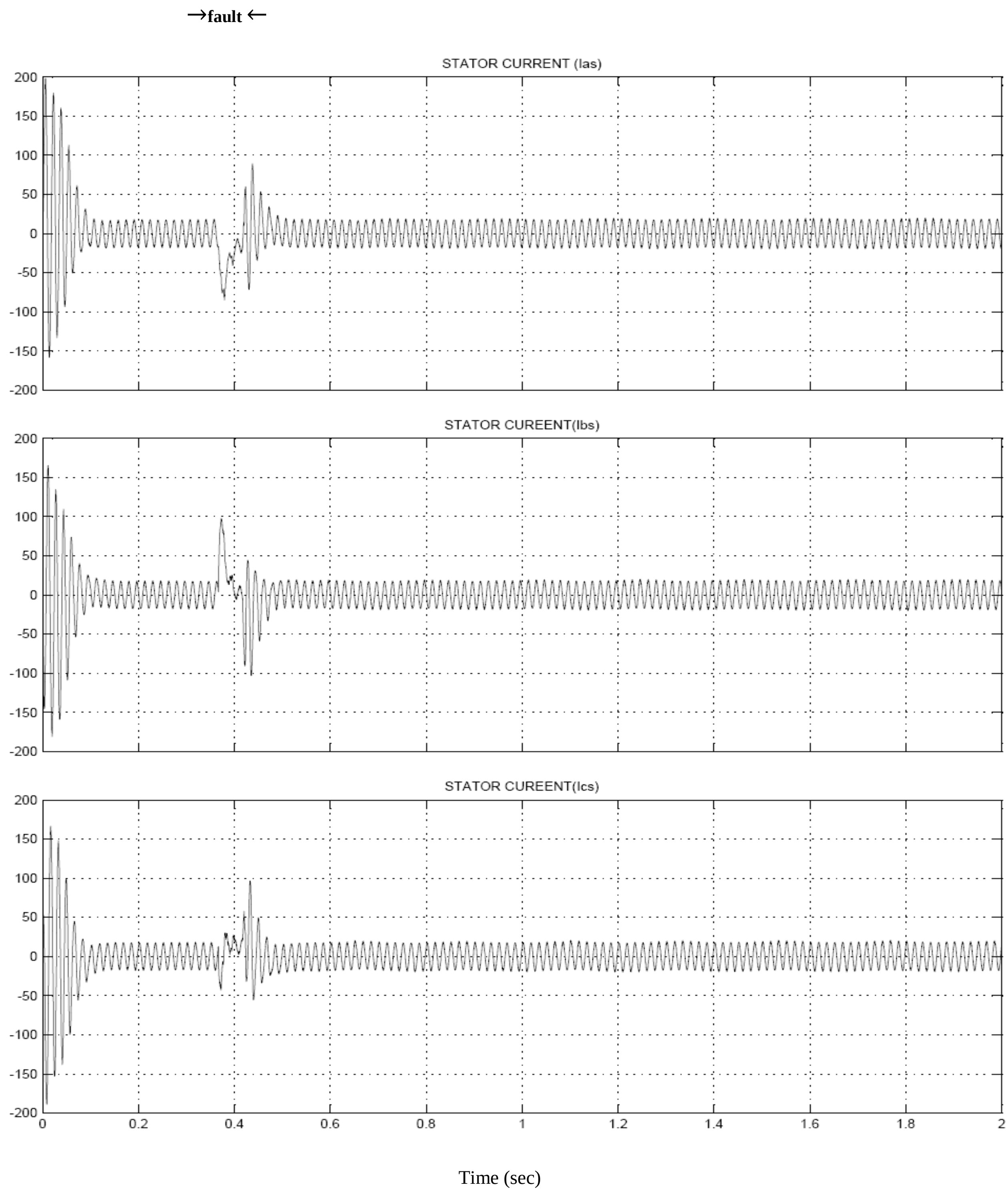


Fig .5.3.2 stator currents ($i_{as,}i_{bs,}i_{cs,}$) during grid fault

5.3.3 Rotor currents ~ time

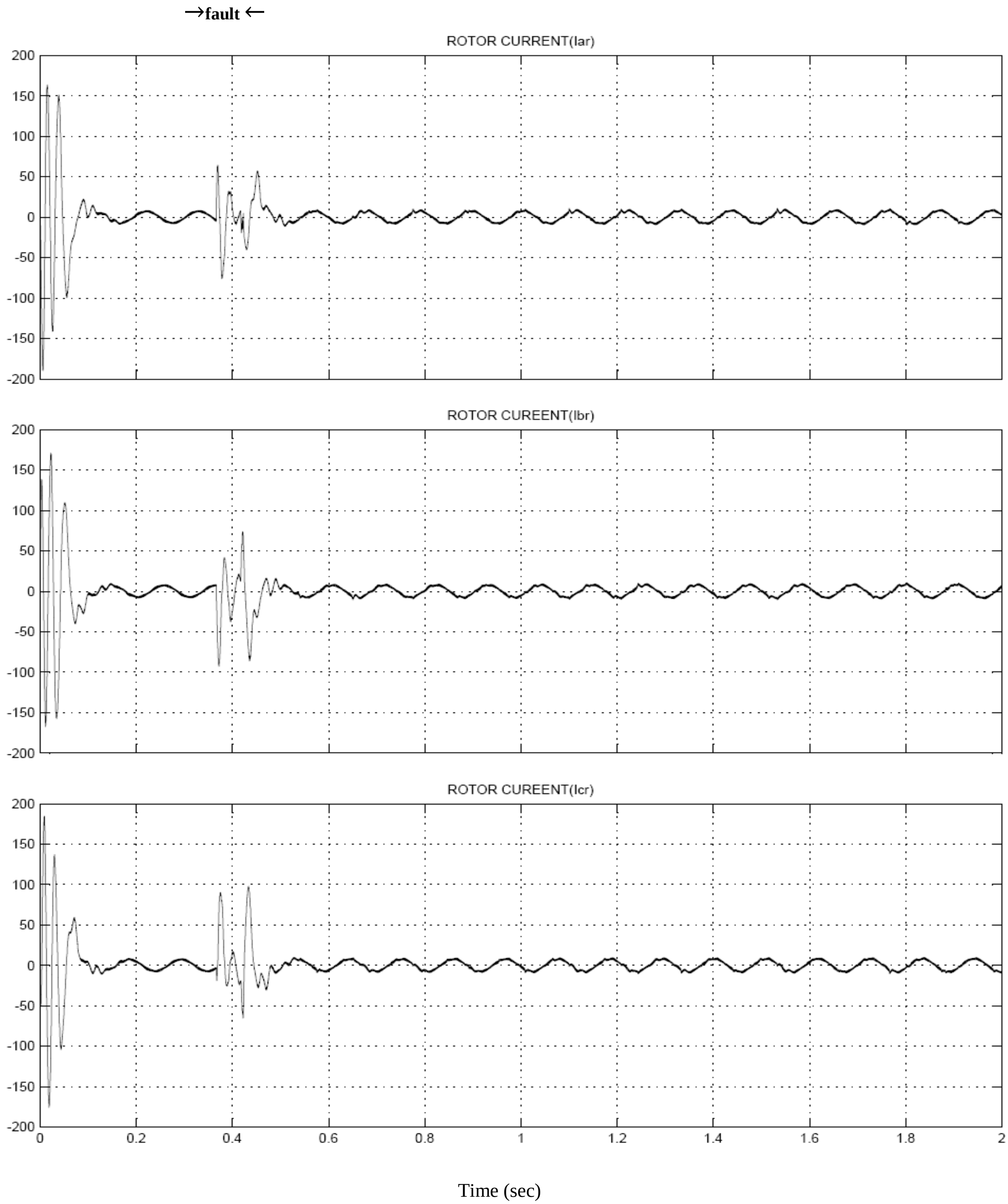


Fig. 5.3.3 rotor currents ($i_{ar,} i_{br,} i_{cr,}$) during grid fault

5.3.4 Speed and electromagnetic torque ~ time

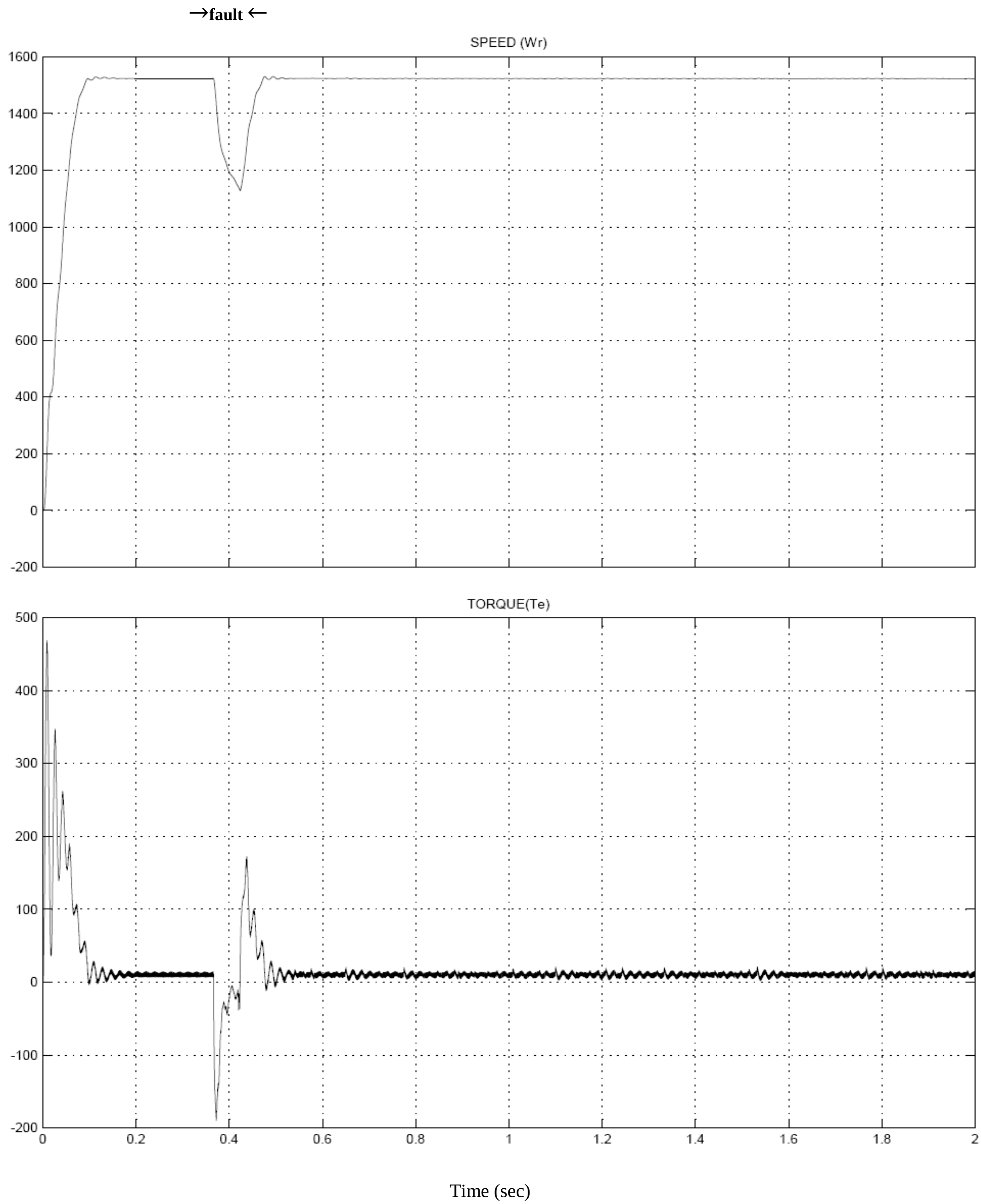
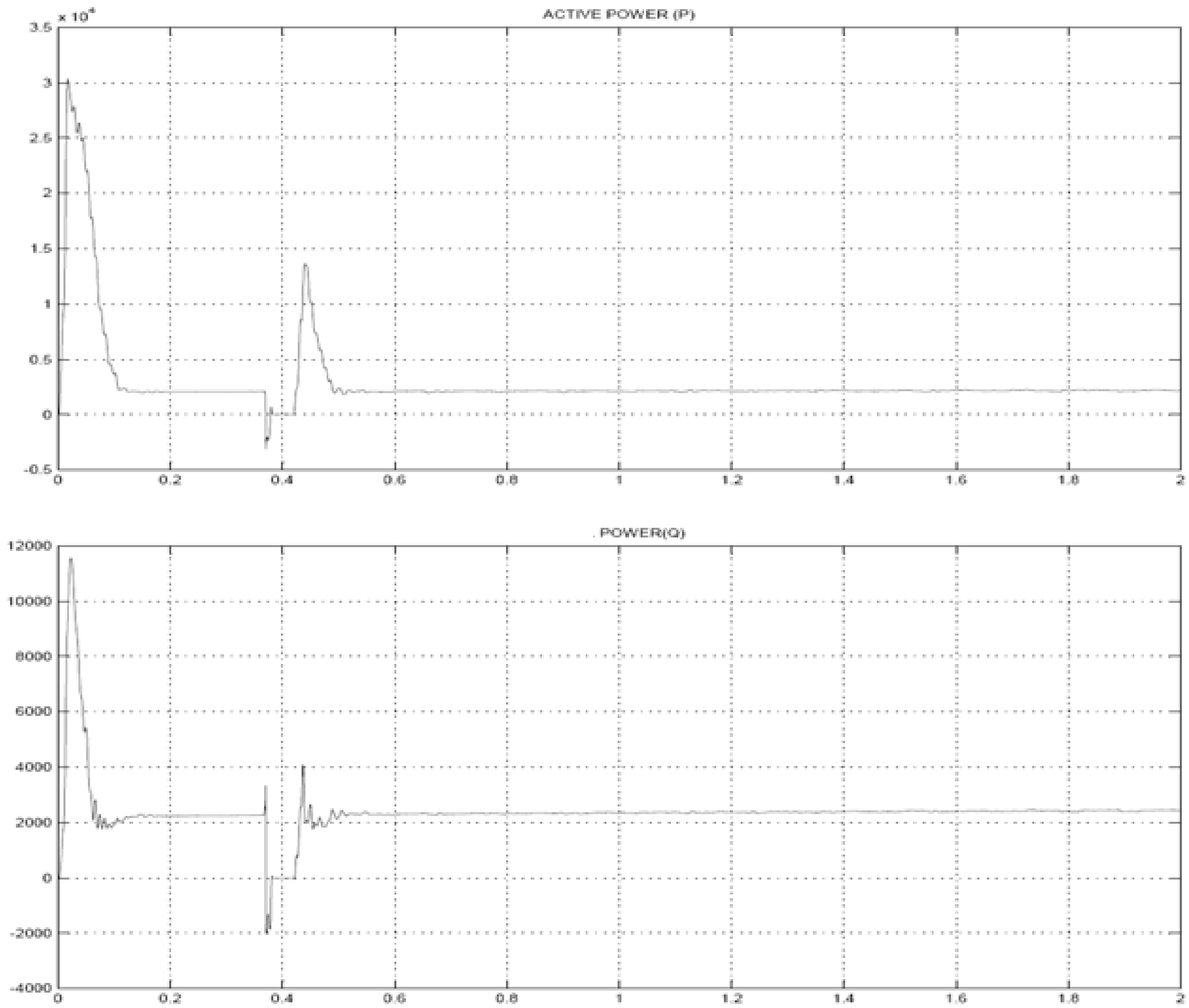


Fig. 5.3.4 speed and torque($\omega_{r,}T_{e,}$) during fault condition

5.3.5 Power characteristics ~ time



Time (sec)

Fig.5.3.5 active power (P) and reactive power (Q) during fault condition

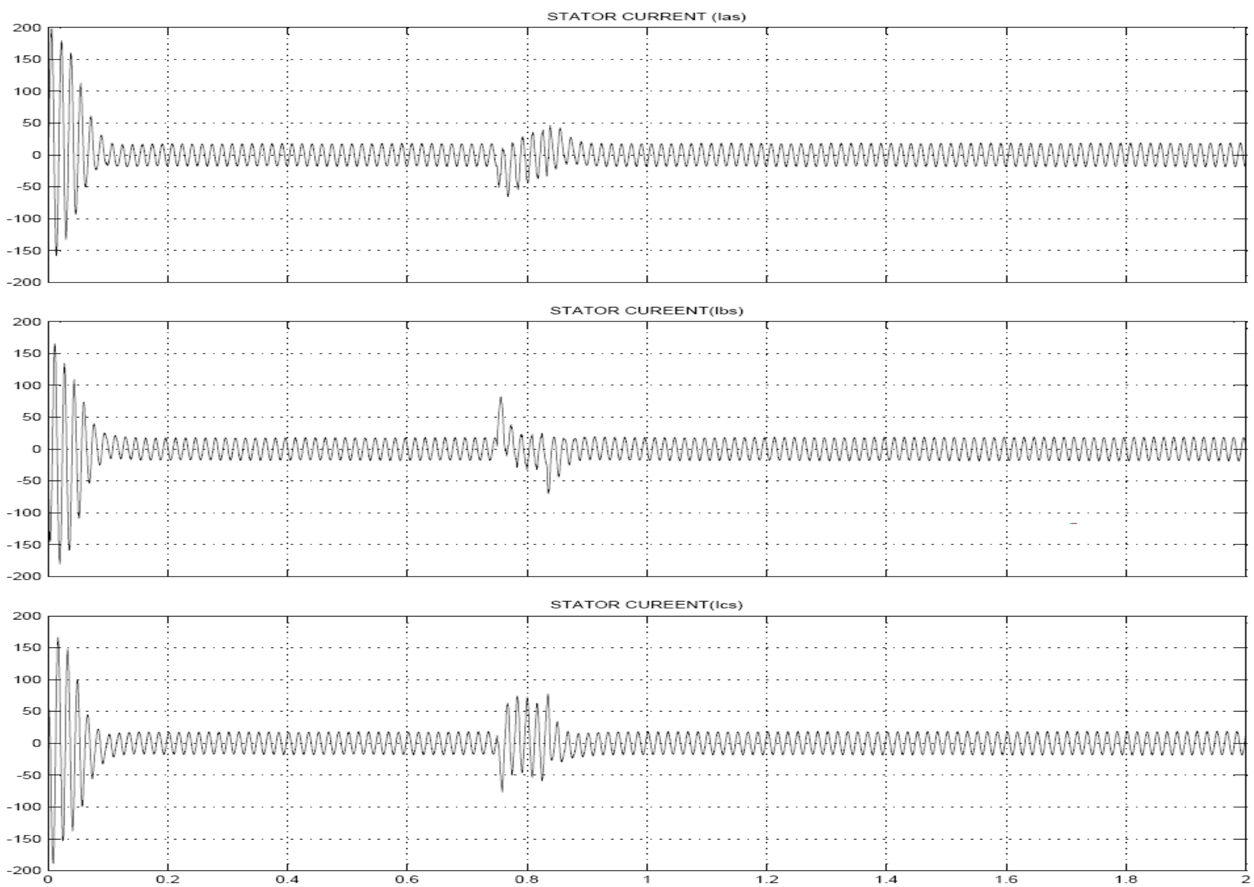
Discussion: 5.3

The dynamic performance of the induction generator is shown respectively in figures 5.3.2, 5.3.3, 4, and 5 during a 3 phase fault at terminals. Initially generator is operating at essentially rated condition with a load torque to base torque. The 3-phase fault at the terminals is simulated by setting $v_{as,}v_{bs,}$and $v_{cs,}$ to zero at the instant $v_{as,}$ passes through zero going positive. After few cycle the source voltage reapplied. The stepping of the terminal voltages to zero shown in fig. 5.3.1 at the time of the fault shown in figures gives rise to decaying in both stator and rotor currents shown in fig. 5.3.2, fig.5.3.3. These transient offsets in the stator currents appear in the rotor circuits as decaying oscillations of near 60hz(because the rotor speed is slightly less than synchronous) shown fig 5.3.4 which are superimposed upon the transients of the rotor circuits. Similarly the transient offset in the rotor currents appears as decaying to the rotor speed. In case of these machines, both stator and rotor transient are highly damped and subside before the fault is removed and the voltages reapplied. The electromagnetic torque is, of course damping in fig. 5.3.4.

5.4 WIND TURBINE DFIG DURING UNBALANCE CONDITION

<u>Condition</u> – 1 when the sudden change of dynamic load is applied for few cycles.

5.4.1 Stator currents ~ time



Time (sec)

Fig .5.4.1 stator currents ($i_{as,} i_{bs,} i_{cs,}$) during dynamic loading

5.4.2 Rotor currents ~ time

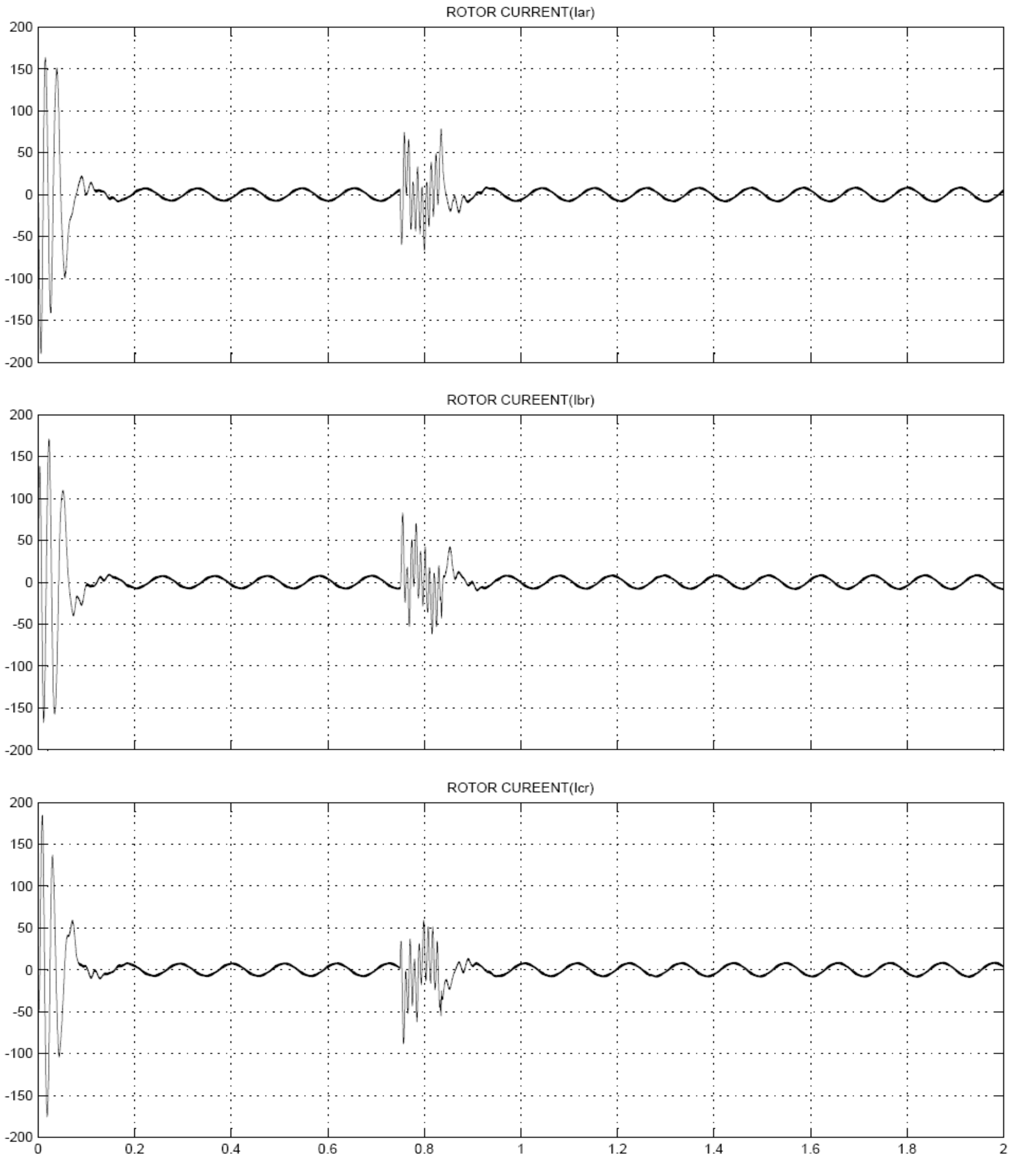
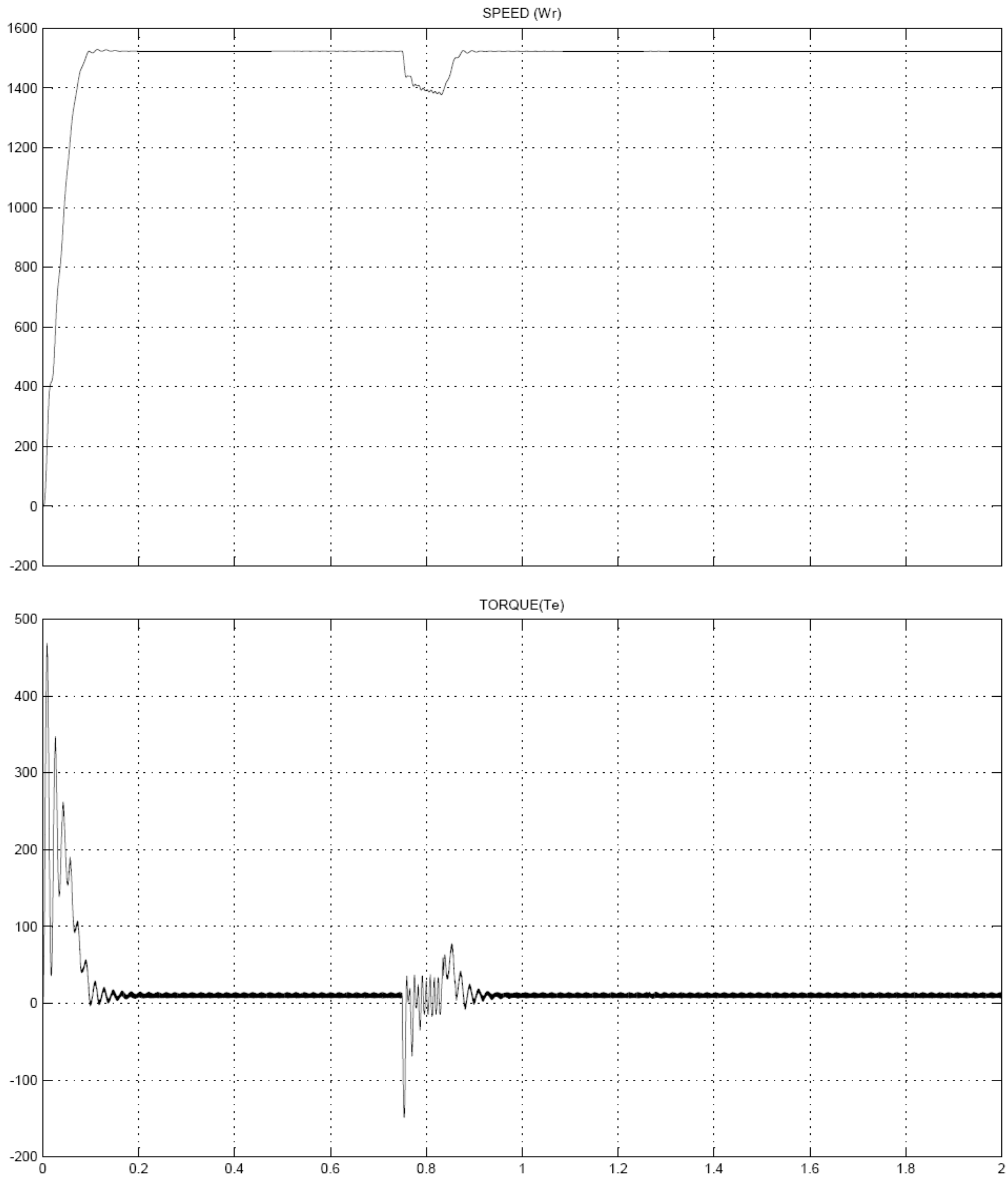


Fig. 5.4.2 rotor currents ($i_{ar,}i_{br,}i_{cr,}$) during dynamic loading

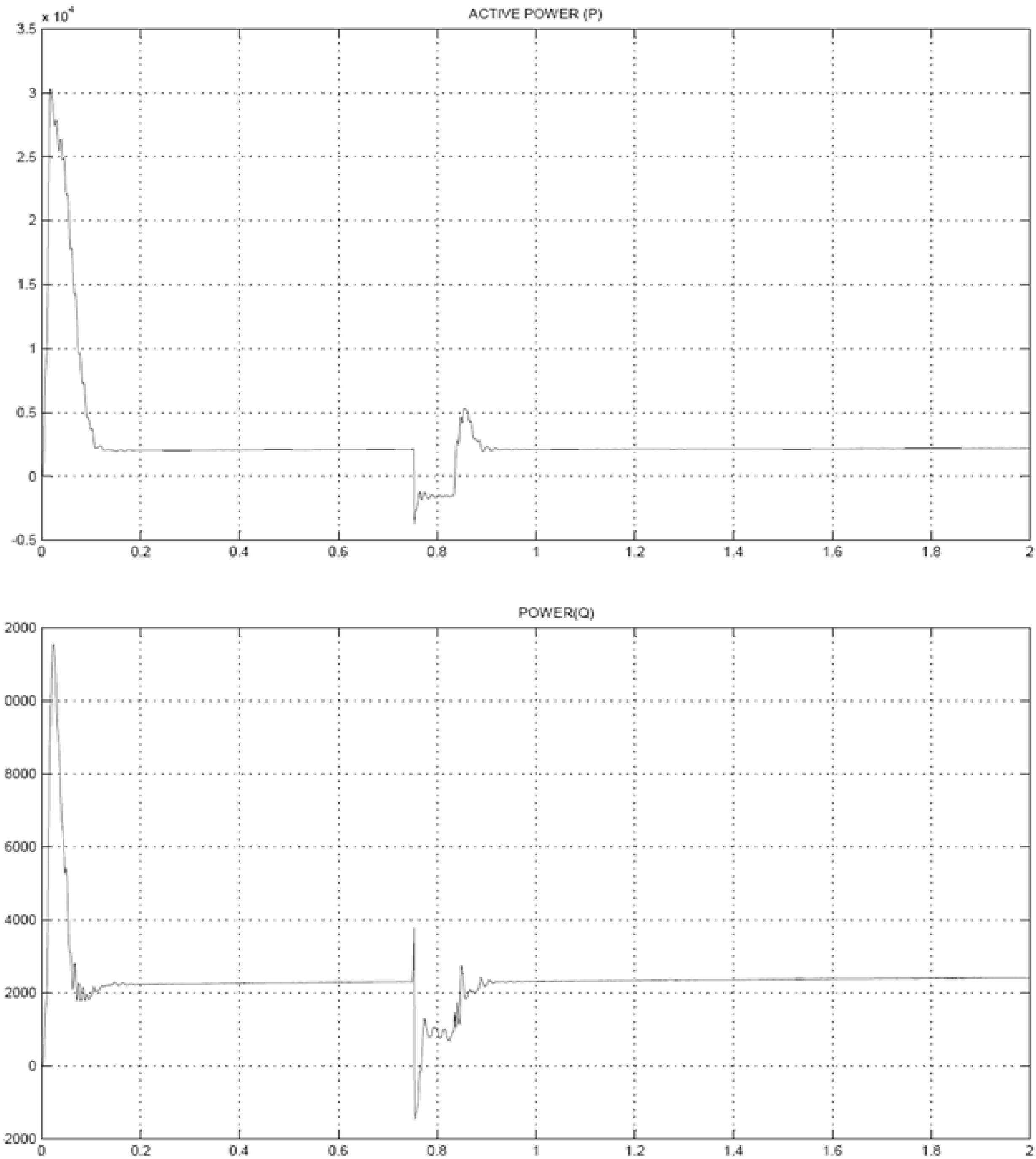
5.4.3 Speed and electromagnetic torque ~ time



Time (sec)

Fig. 5.4.3 speed and torque($\omega_{r,}T_{e,}$) during dynamic loading

5.4.4 Power characteristics ~ time



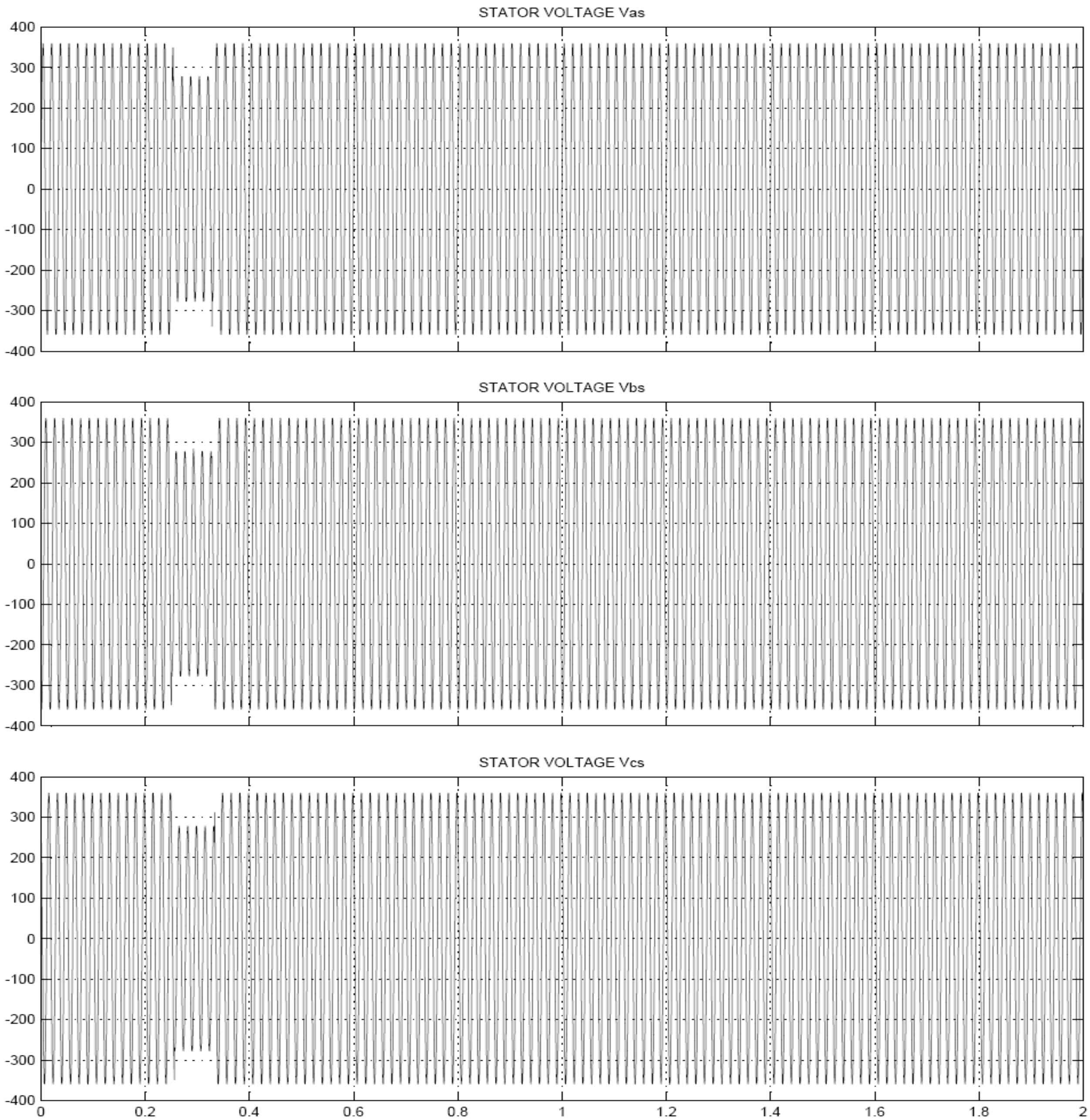
Time (sec)

Fig.5.4.4 active power (P) and reactive power (Q) during dynamic loading

<u>Condition</u> – 2 when the voltage sag (voltage dip) is created for a little cycle. It is a sudden reduction (between 10% and 90%) of terminal voltage.

5.4.5 Stator voltages ~ time

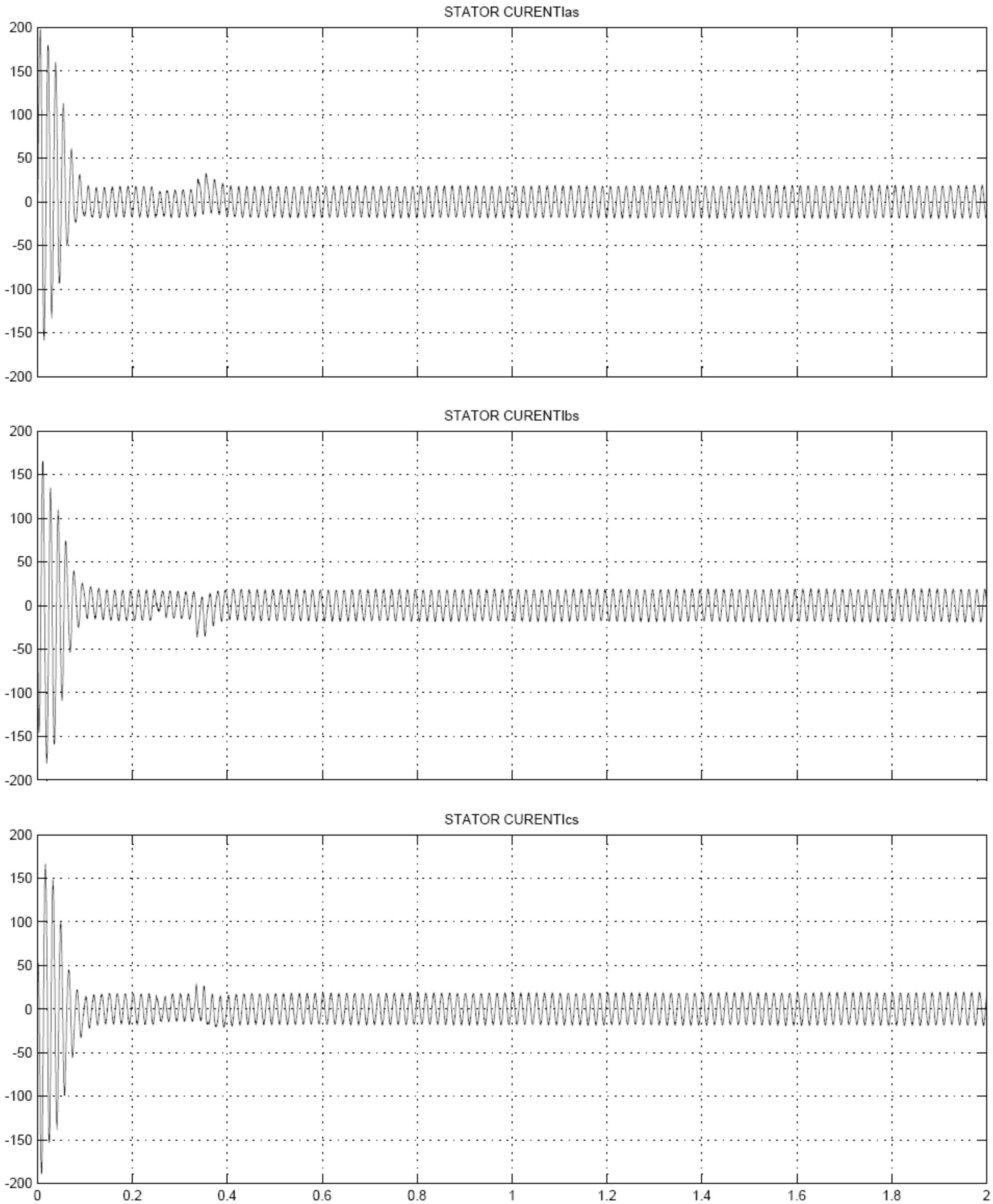
→seg ←



Time (sec)

Fig. 5.4.5 stator voltages $v_{as,}v_{bs,}v_{cs,}$ during voltage dip

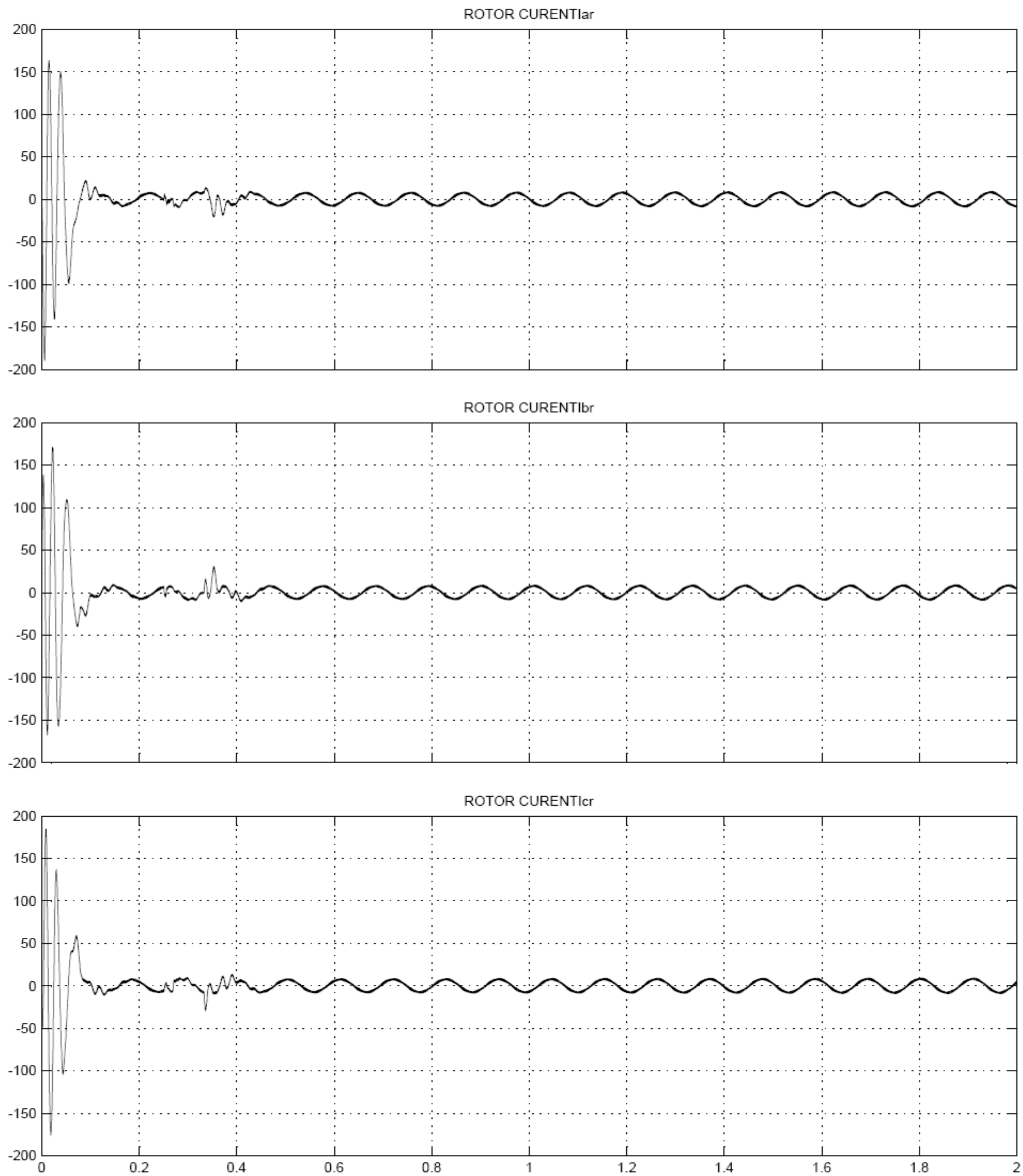
5.4.6 Stator currents ~ time



Time (sec)

Fig .5.4.6 stator currents ($i_{as,}i_{bs,}i_{cs,}$) during voltage dip

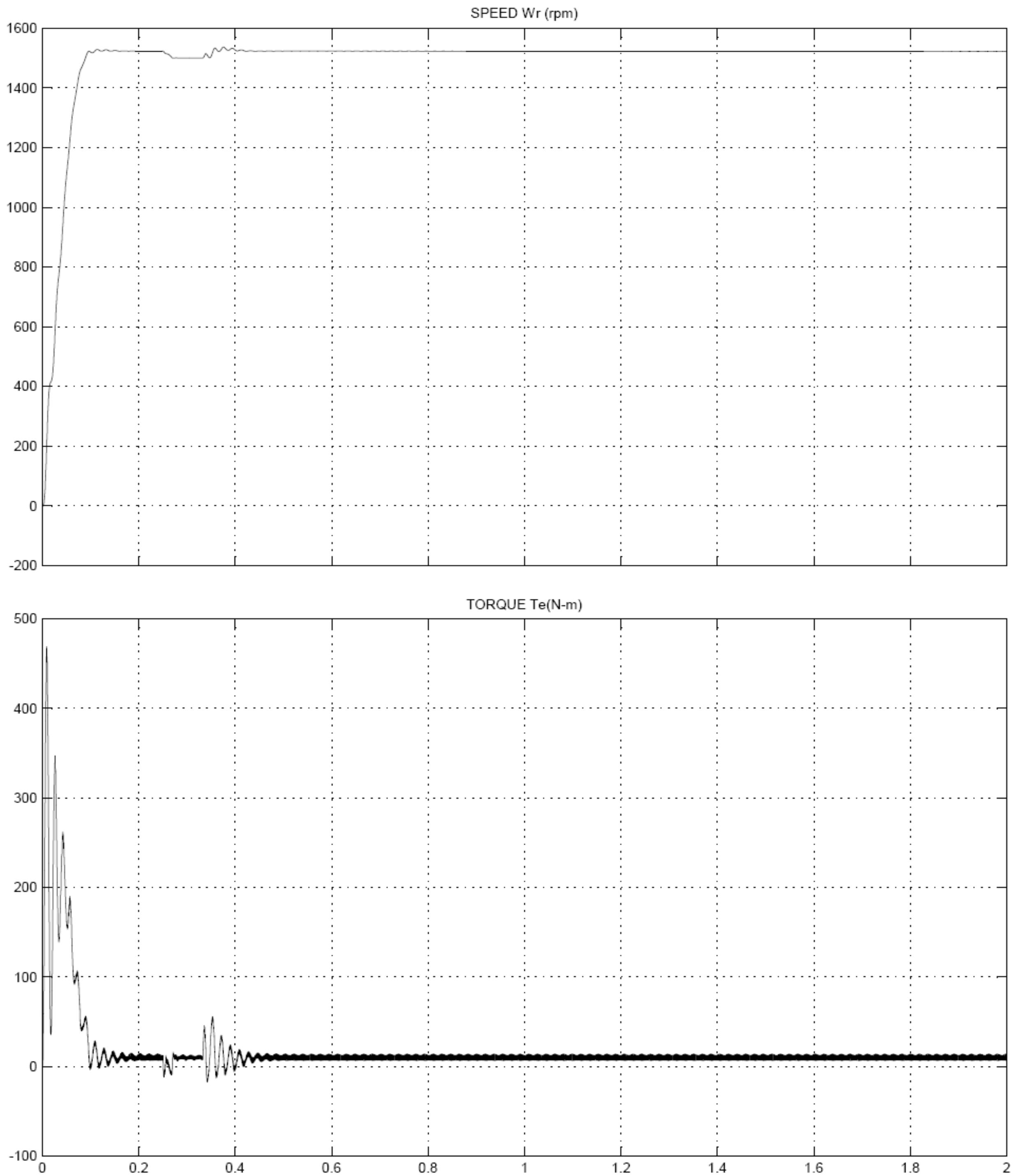
5.4.7 Rotor currents ~ time



Time (sec)

Fig. 5.4.7 rotor currents ($i_{ar,} i_{br,} i_{cr,}$) during voltage dip

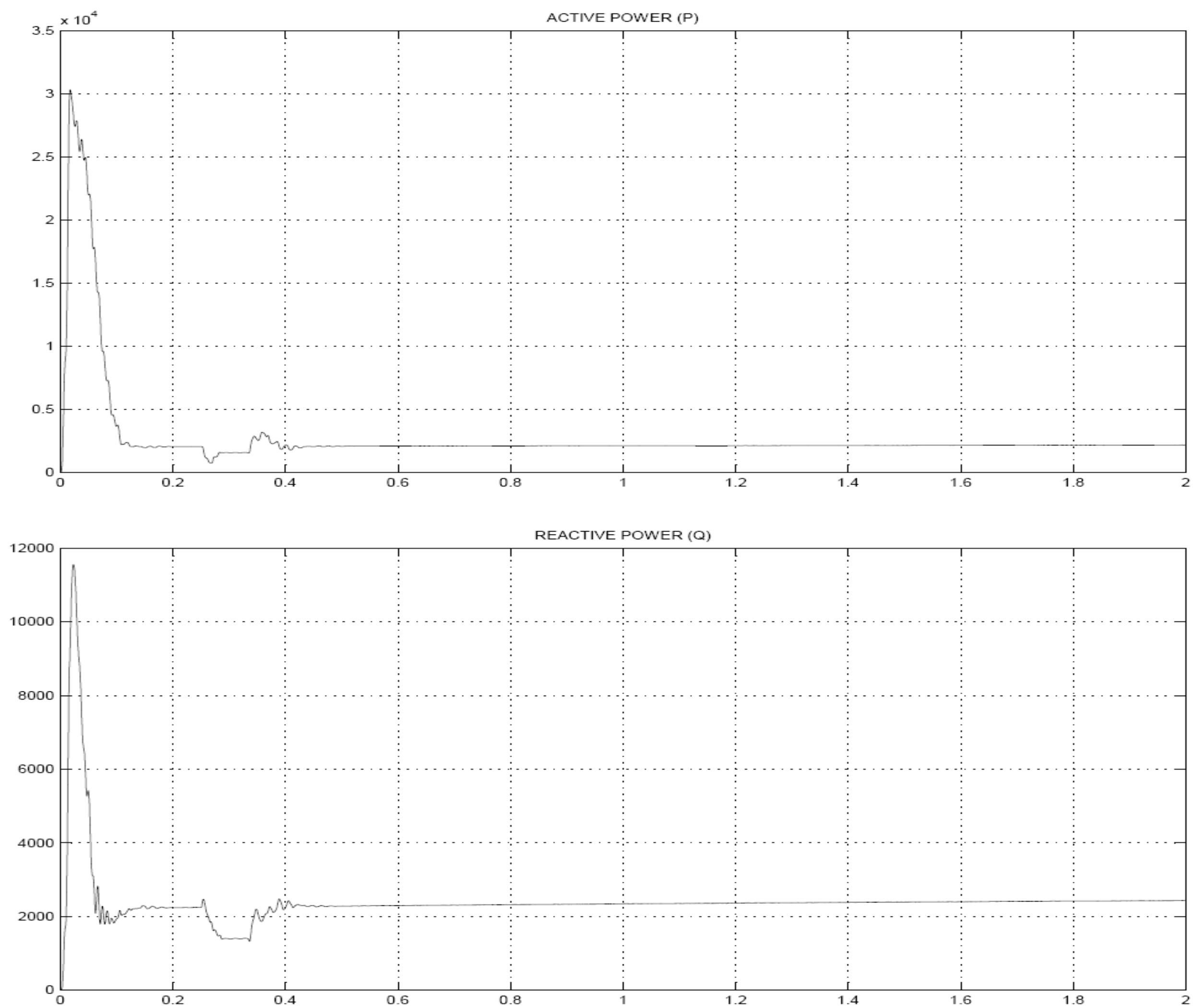
5.4.8 Speed and electromagnetic torque ~ time



Time (sec)

Fig. 5.4.8 speed and torque($\omega_{r,} T_{e,}$) during voltage dip

5.4.9 Power characteristics ~ time



Time (sec)

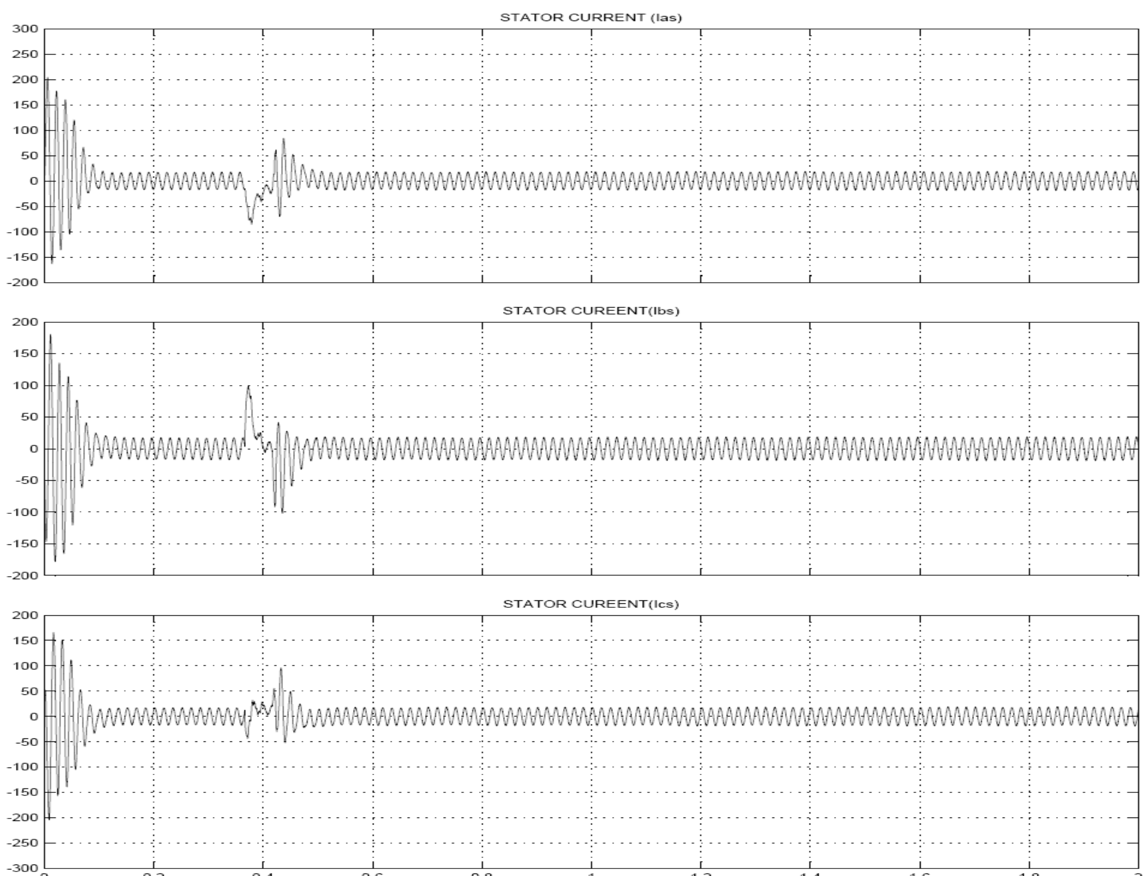
Fig.5.4.9 active power (P) and reactive power (Q) during voltage dip

Discussion: 5.4

The dynamic behavior of the machine during sudden changes in load shown in fig. 5.4.1. 5.4.2., 5.4.3 and 5.4.4 respectively. Initially the generating operating at synchronous speed. The load torque is first stepped from zero to base torque (slightly less than rated) and the generator allowed establish this new operating point. Next the load torque is stepped from base torque back to zero whereupon the generator reestablishes its original operating condition. The variable of the machine approach each new operating in an over damped manner. In previous section we found the generator the steady state (balance condition) the torque and speed characteristics nearly same as the free acceleration characteristics. Here we are not surprised to find that dynamics during load changes can be predicted adequately by normal condition speed and torque curves. Due to load changes the terminal voltage is reduced it is depends on the type of load. Therefore the stator current and rotor current increases instantaneously. It is shown in figures 5.4.1 and 5.4.2 and the next unbalance condition by reduction 10% to 90 % of voltage (voltage sag) shown in fig. 5.4.5 here be can observe the small dynamics as compare to step changes load shown in fig. 5.4.6 , 5.4.7 , 5.4.8, 5.4.9

5.5 DC MACHINE COUPLED WITH DFIG DURING FAULT CONDITION

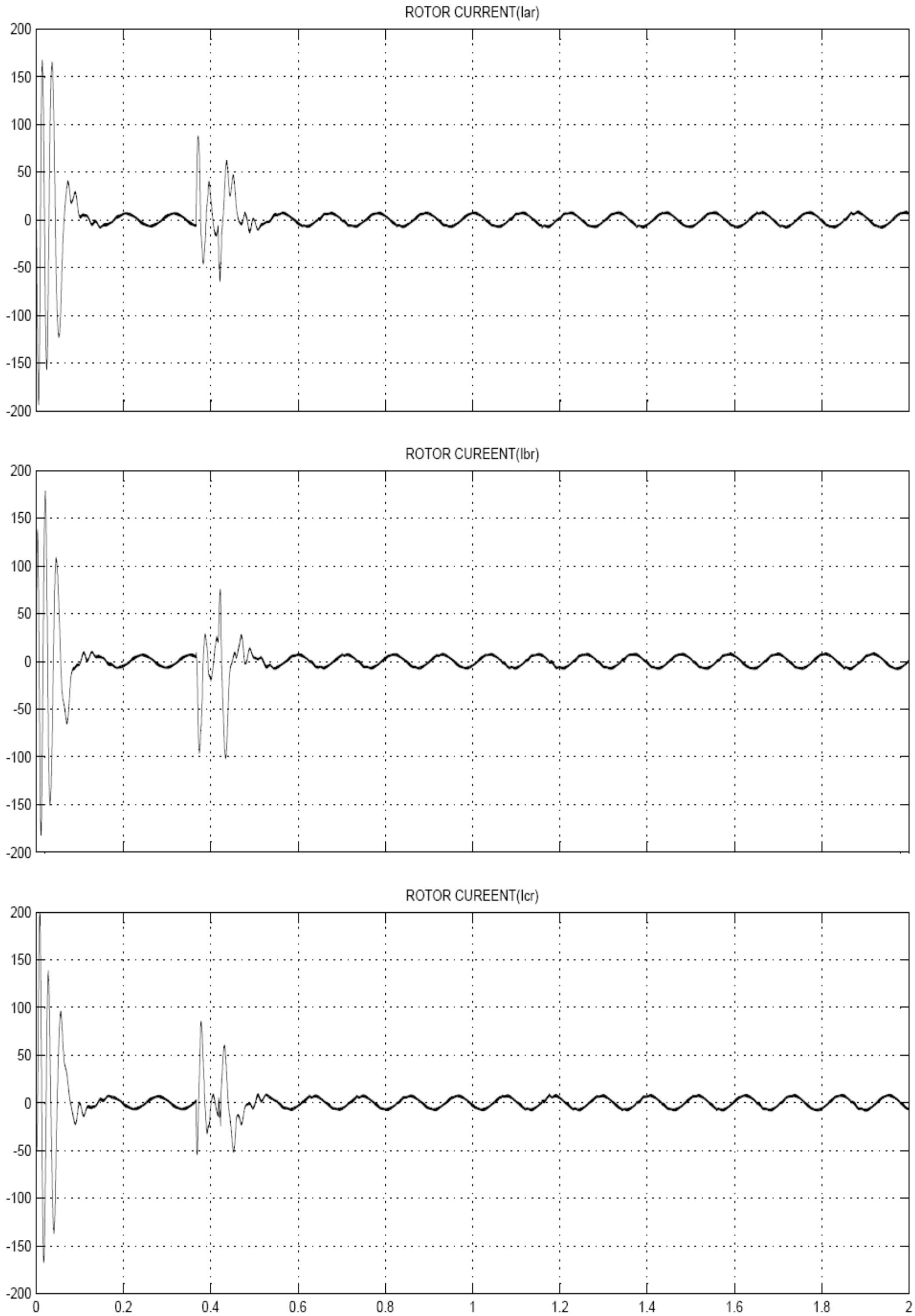
.5.1 Stator currents ~ time



Time (sec)

Fig .5.5.1 stator currents ($i_{as,}i_{bs,}i_{cs,}$) during fault condition

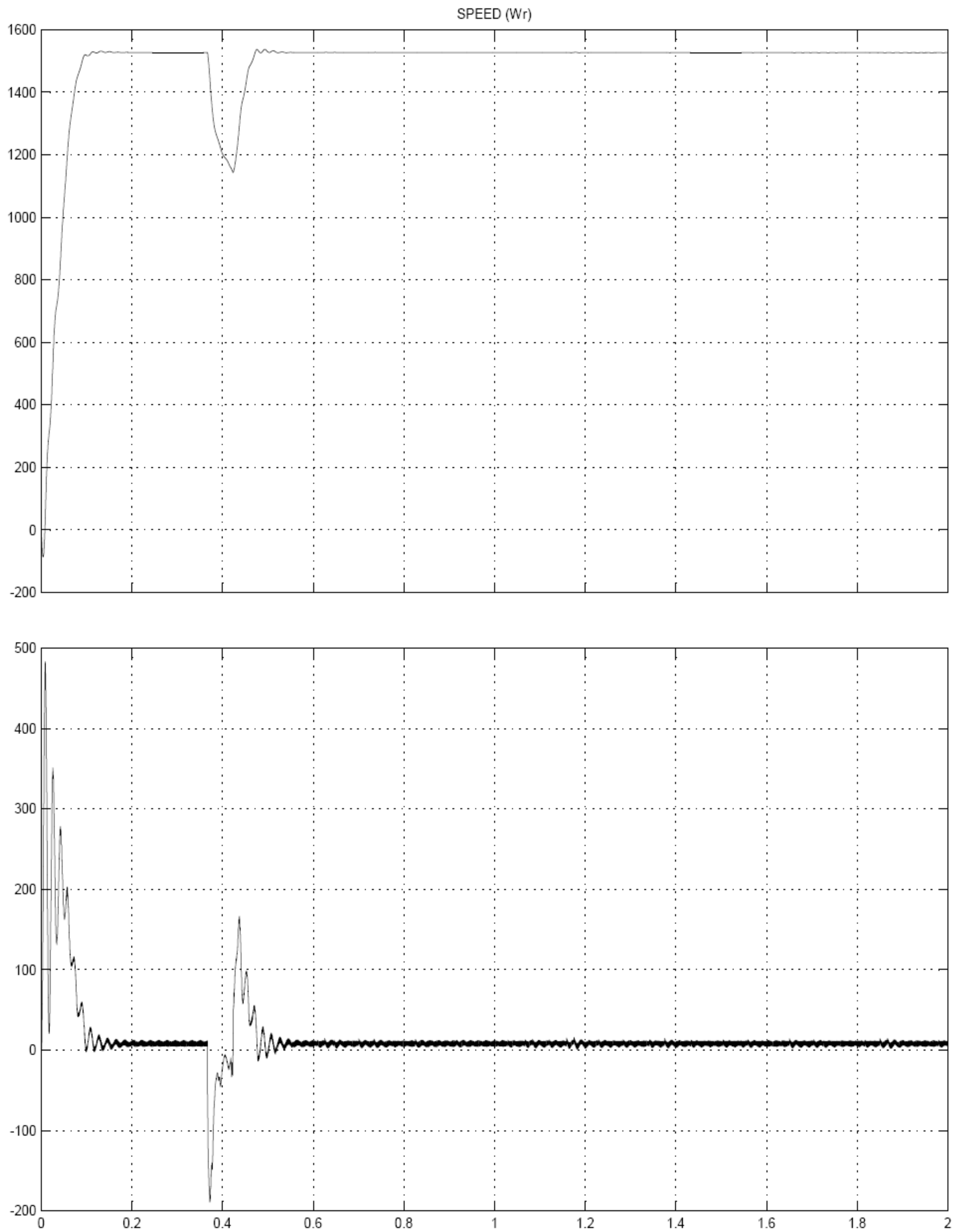
5.5.2 Rotor currents ~ time



Time (sec)

Fig. 5.5.2 rotor currents ($i_{ar,}i_{br,}i_{cr,}$) during fault condition

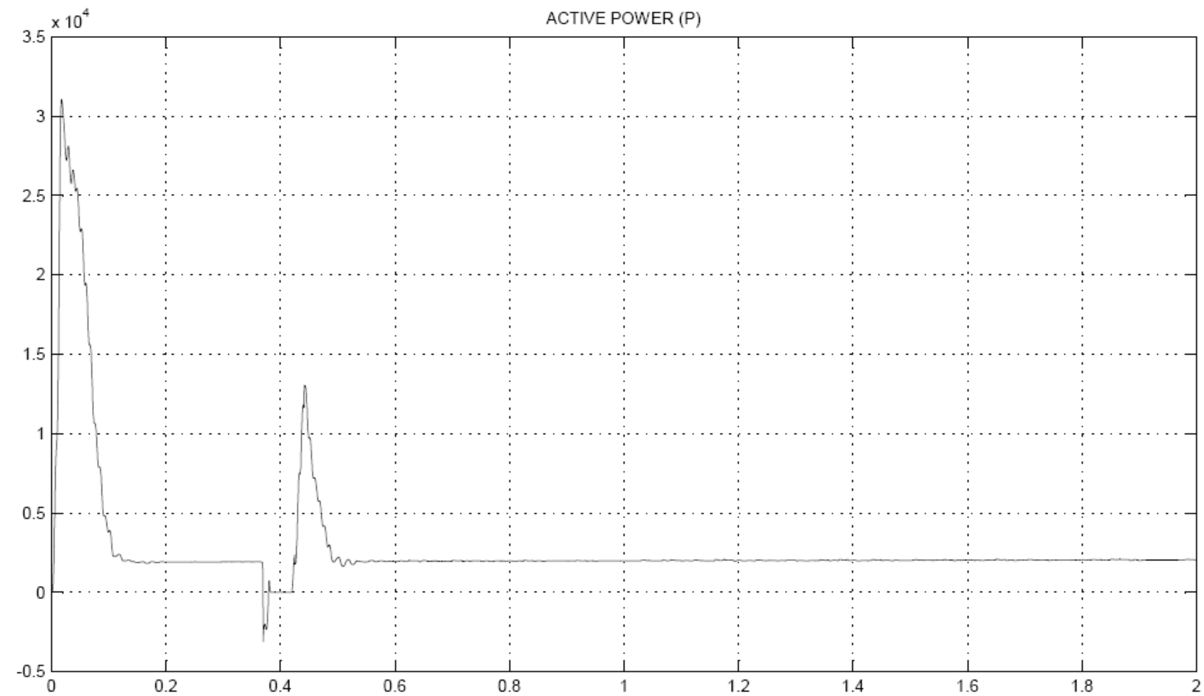
5.5.3 Speed and electromagnetic torque ~ time

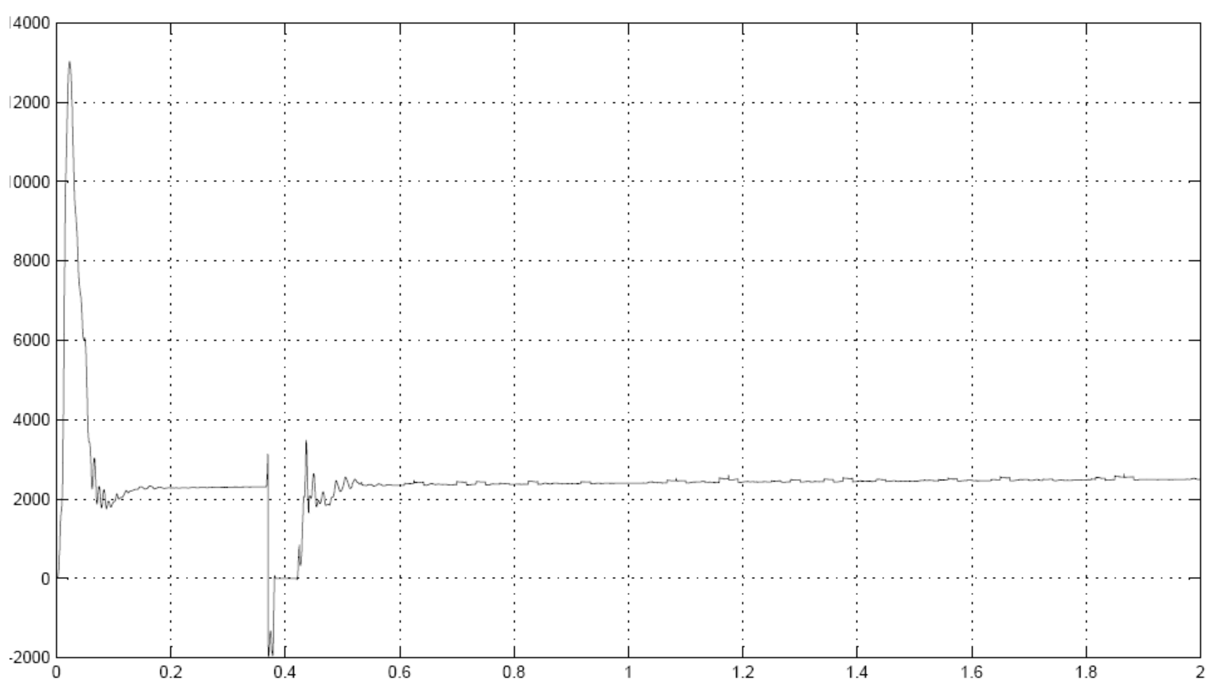


Time (sec)

Fig. 5.5.3 speed and torque($\omega_{r,} T_{e,}$) during fault condition

5.5.4 Power characteristics ~ time



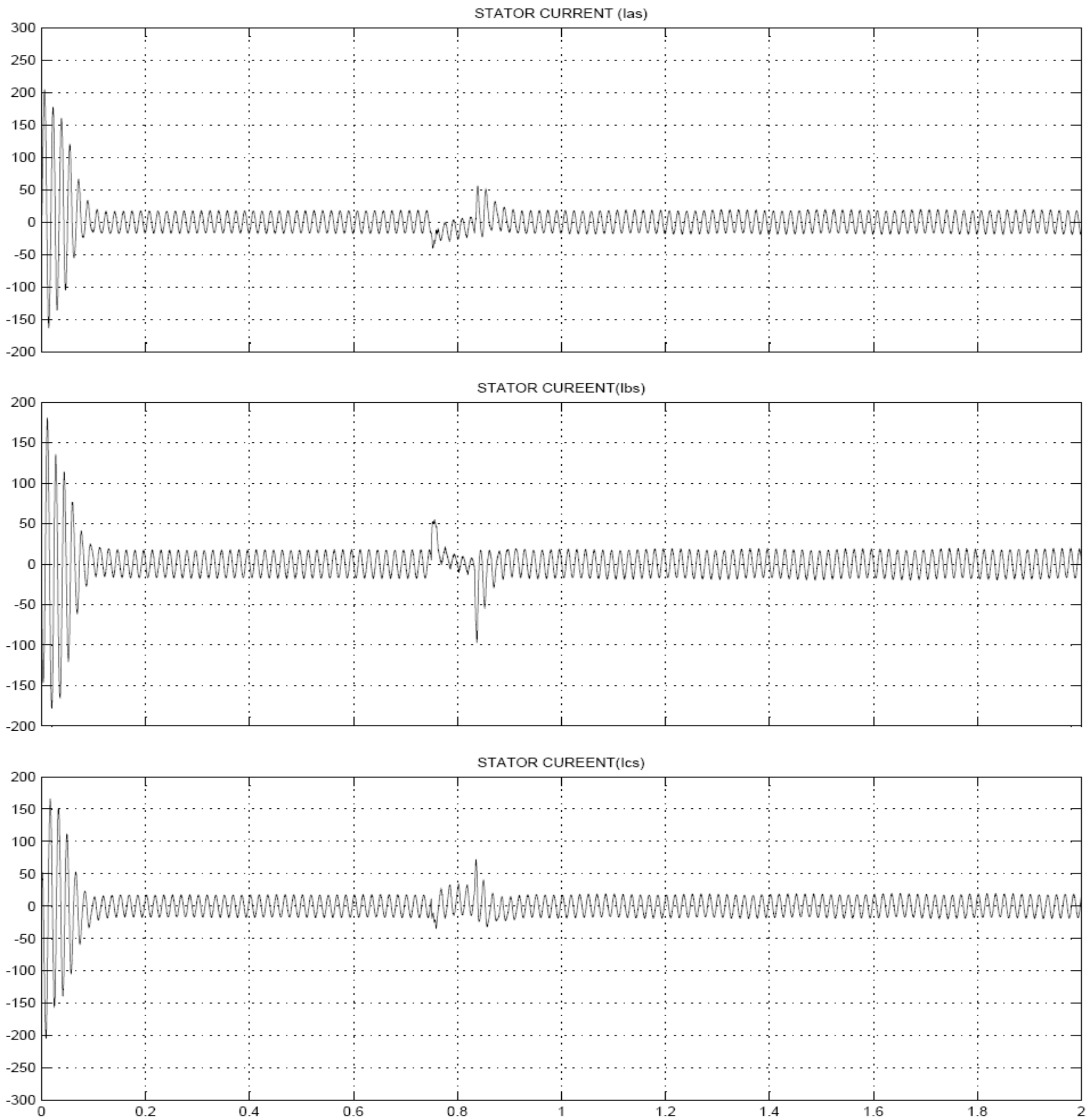


Time (sec)

Fig.5.5.4 active power (P) and reactive power (Q) during fault condition

5.6 DC MACHINE COUPLED WITH DFIG DURING UNBALANCE CONDITION

5.6.1 Stator currents ~ time



Time (sec)

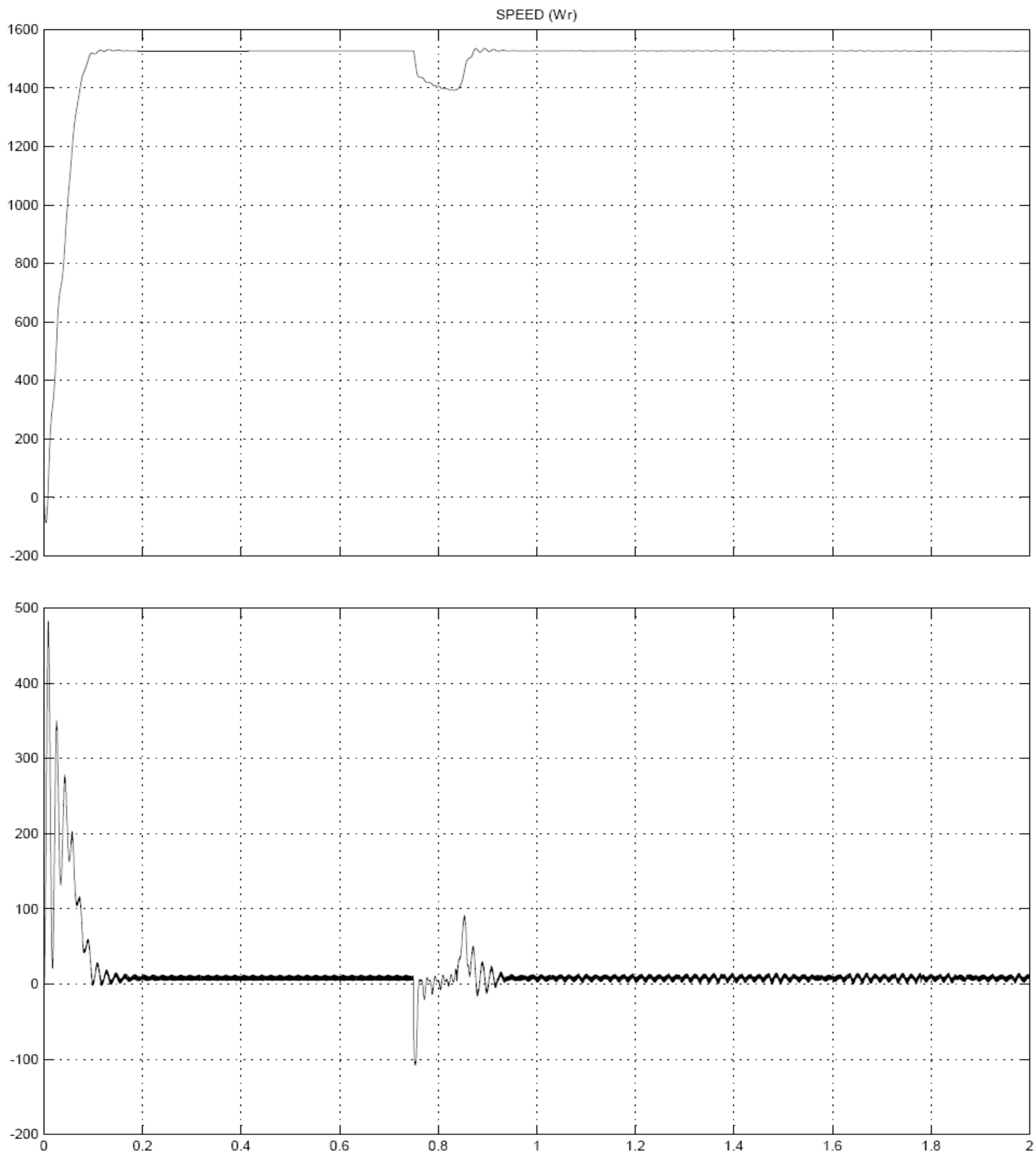
Fig .5.6.1 stator currents ($i_{as,} i_{bs,} i_{cs,}$) during unbalance condition

5.6.2 Rotor currents ~ time

Time (sec)

Fig. 5.6.2 rotor currents ($i_{ar,} i_{br,} i_{cr,}$) during unbalance condition

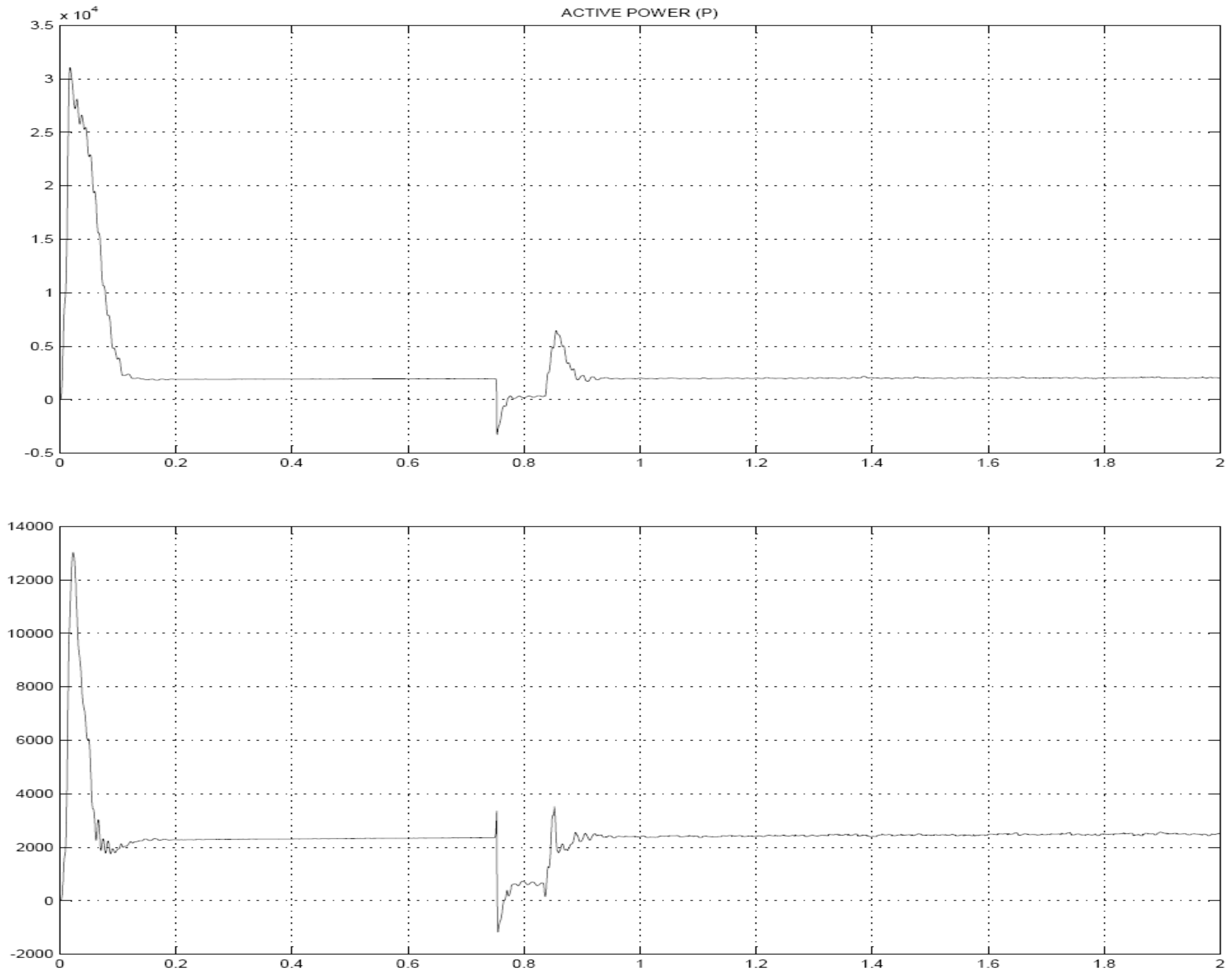
5.6.3 Speed and electromagnetic torque ~ time



Time (sec)

Fig. 5.6.3 Speed and torque(ω_r, T_e) during unbalance condition

5.6.4 Power characteristics ~ time



Time (sec)

Fig.5.6.4 active power (P) and reactive power (Q) during unbalance condition

Discussion: 5.5 and 5.6

The dynamic performance of the induction generator coupled with dc machine is shown in figures of section 5.5 and 5.6 respectively during a 3 phase fault and step changes in load. Similarly as in previous section initially generator is operating at essentially rated condition with a load torque to base torque. Dynamic performances of wind turbine with DFIG and dc machine coupled with DFIG are some different transient because of dc machine has different time constant.

CHAPTER 6

CONCLUSION

CONCLUSION

This thesis presents a study of the dynamic performance of variable speed DFIG coupled with either wind turbine or a dc motor and the power system is subjected to disturbances; such as voltage sag, unbalanced operation or short circuit faults. The dynamic behavior of DFIG under power system disturbance was simulated both using MATLAB coding and MATLAB/SIMULINK platform using matrix /vector space control concept. Accurate transient simulations are required to investigate the influence of the wind power on the power system stability.

The DFIG considered in this analysis is a wound rotor induction generator with slip rings. The stator is directly connected to the grid and the rotor is interface via a back to back partial scale power converter (VSC). Power converter are usually controlled utilizing vector control techniques which allow the decoupled control of both active and reactive power flow to the grid. In the present investigation, the dynamic DFIG performance is presented for both normal and abnormal grid conditions. The control performance of DFIG is satisfactory in normal grid conditions and it is found that, both active and reactive power maintains a study pattern in spite of fluctuating wind speed and net electrical power supplied to grid is maintained constant. During grid disturbance, considerable torque pulsation of DFIG and torsional oscillation in drive train system has been observed.

The detailed results of steady state and faulty or unbalance grid conditions has been noted and analyzed in chapter 5 with proper justification. In view of that, future scope aims to

- Develop a controller, which can effectively improve the dynamic stability, transient response of the system during faulty grid conditions.
- To develop a protection system for power converter and DFIG for large disturbances like 3-phase fault of little cycle duration as the power converter is very sensitive to grid disturbance.

APPENDIX

Induction generator rating: 3hp (2.23kw), 440 v, 1500 rpm.

R_s= 0.435 ohm

R_r= 0.816 ohm

X_s= 0.446 ohm

X_m= 0.43 ohm

X_s= 0.446 ohm

Number of pole pair (p) = 2

J = 0.08 kg. m^2

Wind turbine data:

Air density ρ = 1.2 kg/m^3

Wind speed v = 10 m/s

DC motor: 5hp, 220v, 1500rpm

R_a= 2.58 ohm

L_a= 0.028 H

R_f= 30.8 ohm

L_f= 2.156 H

L_{af}= 0.9483

J=0.02215 kg. m^2

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